

Dams, fish and fisheries

Opportunities, challenges
and conflict resolution

edited by

Gerd Marmulla

Fishery Resources Officer

Inland Water Resources and Aquaculture Service

Fishery Resources Division

FAO Fisheries Department

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PREPARATION OF THIS DOCUMENT

This FAO Fisheries Technical Paper has been prepared to publish information that was compiled as a working paper for the World Commission on Dams (WCD). The material presented herein was previously submitted to WCD as FAO's contribution to the Thematic Reviews on Environmental Issues, initiated by WCD in their process of reviewing the various impacts and benefits of dams while preparing a global review on "Dams and Development". The World Commission on Dams had entrusted FAO to review, and to report upon, major fishery issues in relation to world dams. As agreed, the report delivered to WCD contained four individual reviews that had been prepared to address the following complexes of questions:

Have reservoir fisheries been successful in replacing river fisheries?

Which migration mitigation measures exist and how effective are they?

What is the information base and capacity required for effective management of fisheries through a dam project cycle (appraisal, design, construction, operation)?

What are the existing criteria and guidelines concerning dams and fisheries?

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ABSTRACT

The four papers presented in this publication address major fishery issues in relation to dams as identified by the World Commission on Dams (WCD) and FAO for the purpose of WCD's global review on "Dams and Development". Characteristics of river and reservoir fisheries in various regions of the world are reviewed. As reservoirs provide significant contributions to global freshwater fisheries, production figures for reservoirs in Africa, Asia, Latin America and the Caribbean, as well as for the Commonwealth of Independent States, are mentioned. Also fish production figures for large rivers are provided, emphasizing the importance of floodplains for fish production. The extent to which fisheries can be developed, sustained or protected along riverine ecosystems modified by dams reflects basin topography, geological features, watershed hydrology, and climate, as well as engineering features of the dam itself, and operational programmes for retention and release of water from the reservoir, through the dam and into the tailwaters. Compensation for loss in yield from river fisheries can be difficult to achieve through development of reservoir fisheries. Even if compensation is achieved from a fishery perspective, specific needs of fish species that are not included in the fishery, but are threatened or endangered, must be considered to avoid negative impacts to these fishes. The importance of free longitudinal passage of river fauna is stressed. The construction of dams can block or delay upstream fish migration and thus contribute to the decline and even the extinction of species that depend on longitudinal movements along the stream continuum during certain phases of their life cycle. Mortality resulting from downstream passage through hydraulic turbines or over spillways can be significant. Habitat loss or alteration, discharge modifications, changes in water quality and temperature, increased predation pressure, as well as delays in migration caused by dams, are discussed. Various technical solutions are suggested and critical points, that have to be considered in fishpass construction, are stressed. A non-exhaustive review of the current status of the use of fish facilities at dams throughout the world is presented, with the main target species considered from North America, Europe, Latin America, Africa, Australia, New Zealand, Japan and Asia. The main challenges to maintaining and enhancing reservoir fisheries, as well as associated social and economic benefits, are fish habitat and environmental degradation, inadequate fish assemblages, inefficient harvesting systems, stakeholder conflicts, and insufficient institutional and political recognition. Fishery administrators find it difficult to defend the interests of their sector; decisions over developments affecting fisheries and aquatic environments are often made with minimum or no consideration of these sectors, mainly for lack of reliable economic valuation and lack of political clout by the users. Given this lack of political power, the interests and needs of fishers and fisheries managers are often not properly represented within existing political frameworks, and thus neglected or ignored. Fishery administrators and stakeholders should seek every opportunity to communicate their needs and demonstrate the value of fisheries and the aquatic natural resources. The multi-sectoral nature of water resources development in the context of socio-economic development must be recognized. Management policy must be country-specific and take local conditions into account as blind application of imported principles may lead to policy failures. Fisheries management capacity and information base requirements are reviewed for the six phases of the dam project cycle, i.e. dam identification, dam design, dam project appraisal, dam construction, dam operation and dam decommissioning. Effective environmental assessment and management coupled with improvements in design of civil engineering structures has made some recent dam projects more fish friendly and environmentally acceptable. The need for drafting legal instruments, which will facilitate modification of dam structures to incorporate mitigation measures and help altering dam operation rules to be more beneficial to fish biodiversity and fisheries, is emphasized.

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THE INFLUENCE OF DAMS ON RIVER FISHERIES

by

Donald C. Jackson

**Professor of Fisheries Management
Department of Wildlife and Fisheries
Mississippi State University
Box 9690, Mississippi State, USA**

and

Gerd Marmulla

**Fishery Resources Officer
Inland Water Resources and Aquaculture Service
Food and Agriculture Organization of the United Nations
Viale delle Terme di Caracalla, 00100 Rome, Italy**

EXECUTIVE SUMMARY

The extent to which fisheries can be developed, sustained or protected along riverine ecosystems modified by dams reflects basin topography, geological features, watershed hydrology, and climate, as well as engineering features of the dam itself, and operational programmes for retention and release of water from the reservoir, through the dam and into the tailwaters. Compensation for loss in yield from river fisheries can be difficult to achieve through development of reservoir fisheries. The larger the river, and the more downstream the location of the dam, the less potential there is for a reservoir fishery to compensate in terms of yield for losses sustained by the river fishery. Compensation potentials apparently are higher in shallower reservoirs in tropical regions than they are in deeper reservoirs and in more northern latitudes. Even if compensation is achieved from a fishery perspective, specific needs of fish species not included in the fishery, and/or that may be threatened or endangered, must be considered to avoid negative impacts to these fishes.

There is considerable variability in fishery production among and within regions with respect to reservoir and river fisheries. River fishery production is dependent on length of river, catchment area and, for specific sections of rivers, the position of the segment along the river continuum. In tropical and temperate rivers, fish yields per unit surface area are considerably greater in rivers with flood pulses and floodplains than in nearby impoundments where flood pulses are reduced or absent. In the tropics, for example, large, slow-flowing rivers averaged 30-100 kg/ha/year and the floodplains averaged 200-2 000 kg/ha/year. Fish yields in floodplain river ecosystems are directly related to the height and duration of floods. If altered hydrology resulting from dams curtails or eliminates normal, historical downstream flooding, overall fisheries production throughout the system can be negatively impacted.

In Africa, large reservoirs subject to moderate to heavy fishing (e.g. Kariba, Nasser/Nubia, Volta), have yields ranging 27-65 kg/ha/year. In contrast, however, Lake Kainji, another large African reservoir has yields of only 3.5-4.7 kg/ha/year. For medium-sized African reservoirs, estimated mean yield was approximately 80 kg/ha/year. Mean yield from a variety of Sub-Saharan small water bodies was 329 kg/ha/year. Substantial overall losses to overall fishery production in river basins have been reported as a result of dam construction in Africa. For example, an annual net loss of 11 250 t of fish per year were lost in the Senegal River system as a result of dam construction associated with Lake de Guiers.

Major concern throughout Asia is that movements of migratory fishes along river courses will be blocked by dams. Additionally, dewatering of stream channels immediately downstream from dams can be a serious problem. Reservoir yields in China are reported to range from 127 to 152 kg/ha/year, but these high values tend to be the result of intensive stocking programmes. In India reservoir fishery yields range from 11.4 (large reservoirs) to 49.5 (small reservoirs) kg/ha/year. Reservoir fishery yields in Southeast Asia (e.g. Malaysia) and Central Asia and Kazakhstan are reported to be much less than in other parts of Asia, with values typically around 15 kg/ha/year or less. Yields in Sri Lanka range from 40 to 650 kg/ha/year, but these yields are primarily the result of stocking reservoirs with exotic species.

In Australia, dams have generally resulted in negative impacts to native riverine fishes while encouraging exotic species. This has been attributed, in part, to disruption of seasonal flood cycles, and to dams acting as barriers to fish movements. The Murray River now has the lowest commercial fish yield per km² of floodplain of any of the world's major rivers, although historical catches were comparable. In reservoirs constructed on Queensland rivers, fish stocks are maintained through stocking of native fish species.

In Latin America and the Caribbean, reservoir fishery yields tend to be higher for the Caribbean (Cuba 125 kg/ha/year; Dominican Republic 29-75 kg/ha/year) than is generally recorded for Central and South America reservoirs. Records available for Brazil (2.1-11.5 kg/ha/year) and Panama (4.8-63.2 kg/ha/year), suggest that reservoirs can have quite variable yields, depending on flushing rates, elevation, and basin morphology. Higher yields throughout the region typically result from stocking of exotic species.

Similar patterns exist with regard to fishery yields from reservoirs in temperate zones. The average yield from North American reservoirs is only 24 kg/ha/year. In Europe, records indicate reservoir fishery yields ranging from 21 to 76 kg/ha/year.

Dams can enhance some riverine fisheries, particularly tailwater fisheries immediately below dams that result from discharge of seston (primarily plankton) from the upstream reservoir. However, discharge of seston is typically attenuated quickly downstream from the dam, with corresponding attenuation of the associated fisheries. If discharge is from the hypolimnion of the reservoir, lowered temperatures in the receiving tailwater can curtail or eliminate warmwater river fisheries and require stocking of exotic coldwater species, e.g. salmonids (assuming that the water is sufficiently oxygenated). Productive tailwater fisheries targeting these coldwater fishes can result but generally require supplemental hatchery programmes and introduction of coldwater invertebrates to serve as forage items for these fish. In North America, yield from coldwater tailwater fisheries have been recorded for up to 339 kg/ha/year with fishing effort seven times higher than the respective upstream reservoir. This high amount of effort reflects high standing stock of salmonids in these environments. Some of these coldwater tailwater fisheries can extend considerable distances (e.g. > 150 km downstream from dams in Arkansas, USA).

Reservoirs resulting from construction of dams can in some situations result in productive fisheries. This is particularly true for locations where river fisheries contribute little to overall national fishery yields. Beneficial reservoir fisheries also exist in drier regions where dams are constructed for agricultural irrigation, and fisheries are secondary considerations. Benefits seem more pronounced for smaller, shallower reservoirs that have reasonably high concentrations of dissolved solids and that are located in the upper reaches of their respective river ecosystem. Stocking of exotic species (both in reservoirs and in tailwaters) can enhance yields, as long as the exotic fishes are environmentally sound and culturally acceptable to the surrounding human population. In this regard, caution is warranted in cultures where fishing and fish consumption are non-traditional activities. Building reservoirs in the context of such cultures may not achieve projected fishery benefits even though exploitable fish stocks may exist.

Development of reservoir plankton reflects nutrients captured by the reservoir. This plankton generally relates directly to fisheries production of the respective reservoir. However, when several dams are constructed on upstream tributaries of a river ecosystem, the cumulative effects of these dams can be that of blocking the flow of nutrients originating from the catchment basin from the lower reaches of the ecosystem, thereby negatively affecting fisheries production in downstream portions of the ecosystem (including estuary and marine environments). Dams also can block the flow of nutrients from ocean environments upstream into riverine environments by preventing anadromous fishes that die after spawning (e.g. Pacific salmonids) from depositing these nutrients via carcass decay in upstream reaches.

Furthermore, and if the riverine fishery is sustained by stocks of migrating fishes that become blocked by a dam, the riverine fishery can be severely impacted. If the migrating fishes are anadromous or catadromous species, linked to ocean fisheries, or those of inland seas or large lakes, the negative impacts to these stocks and their associated fisheries can be catastrophic.

Because dams tend to be constructed to enhance socio-economic development activities, they tend to attract people and industry. Subsequently, river ecosystems containing dams must contend with secondary environmental pressures such as increases in pollution as well as increased exploitation and extraction of their resources (primarily water, fish, and substrates), that are independent from and in addition to the direct influences of dams and reservoirs on the physical and biological dimensions of the system.

Determining the impact of dams on river ecosystems and their associated fisheries depends on spatial and temporal scales of interest. If spatial scales are sufficiently large (planetary, continental, perhaps regional and biome), and temporal scales are sufficiently long (decades, centuries, millennia), placing a dam on a river does little more than increase atmospheric water vapour (through evaporation from the reservoir), reduce long-term streamflows downstream, desiccate terrestrial environments, salinate surrounding areas, and shift bio-energetic processes (some of which can lead to floral and faunal extinction at various scales of resolution). We cannot assign the terms “good” or “bad” to any of these phenomena. They simply reflect anthropogenic activity on this planet. However, if we look at smaller spatial and shorter temporal scales, (which we obviously cannot neglect since we have to make decisions that have bearings on the present and future human generations and also on present and future living aquatic resources) we have to keep in mind that dams and their reservoirs (which can under certain circumstances help to better nourish people and make their livelihoods more sustainable) can - if wrongly placed - also lead to significant declines of fisheries and to extinction of aquatic species.

Given sufficient time, geophysical and climatic forces will override and erode the physical influences of dams, and evolutionary forces will alter how life forms interact with the resulting environments. Caution is warranted to avert potential negative impacts from dams with respect to fisheries and associated human interactions with these and other river resources. Such caution underscores the reality that people are depending on us, the scientists, the resource managers, the decision-makers, to be right.

1. INTRODUCTION

Dams interrupt streamflow, and generate hydrological changes along the integrated continuum of river ecosystems (Vannote *et al.*, 1980; Junk *et al.*, 1989) that ultimately can be reflected in their associated fisheries. The most obvious effects from placing dams on rivers result from formation of new lentic or semi-lentic environments upstream from the dam, and tailwater environments downstream from the dam. Both environments can be conducive to the establishment and maintenance of fish stocks appropriate for exploitation by fisheries.



Photo 1: Through the effect of this hydroelectric dam, the fishery of the White River (Arkansas, USA) was converted from a naturally sustained warmwater fishery into an artificially sustained trout fishery dependant on periodic stocking by Government hatcheries. (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

The extent to which fisheries can be developed, sustained or protected along these modified riverine ecosystems reflects basin topography, geological features, watershed hydrology, and climate, as well as engineering features of the dam itself, and operational programmes for retention and release of water from the reservoir, through the dam and into the tailwaters. Fundamental considerations must include establishment and maintenance of habitat for spawning, recruitment and maturation of the fish stocks, and provisions for passage by fishes that during certain phases of their life cycles, depend on longitudinal movements along the stream continuum (FAO, 1998).

In this regard, Bernacsek (1984) provided an excellent summary of design and operational features for dams to address fisheries concerns. Although the emphasis of Bernacsek's paper focused on African reservoirs, the general orientation has applicability to many situations on a global scale. He suggested: (i) maximum possible crest elevation; (ii) discharge structure intakes positioned at highest possible elevation; (iii) discharge water into tailwaters be sufficiently oxygenated to support aquatic fauna; (iv) annual water level fluctuation in the reservoir to be within the range of 2.5-4.0 m; (v) drawdown rate not to exceed 0.6 m/month; and (vi) downstream discharge to include an annual artificial flood event.



Photo 2: A section of the River Perak (Malaysia) has been dewatered downstream of a dam; only few fish are caught in the dewatered stream stretch. (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

Along the stream continuum, dams and their associated upstream reservoirs have downstream effects on riverine environments and, subsequently, diverse influences on downstream fisheries, even beyond the lotic ecosystem. Cumulative effects of dams in catchment basins and tributary streams can significantly block nutrient flow throughout the ecosystem, affecting fisheries production in downstream reservoirs (Welcomme, 1985), river channels (Hess *et al.*, 1982) and estuary and marine environments (Ryder, 1978). Tolmazin (1979) related reduced fish yields in the Black Sea and the Sea of Azov to impoundments on the Danube, Dnieper, and Dniester rivers in Europe and, in line with the orientations of Welcomme (1985), Hess *et al.* (1982), and Ryder (1978), suggested that such patterns reflected dams acting as nutrient traps.

Dams also block the flow of nutrients from ocean environments upstream into riverine environments. This is particularly true of anadromous fishes such as Pacific salmon (*Oncorhynchus* spp.) that die in the rivers after spawning one time. Cederholm *et al.* (1999) give an account of the essential contributions of nutrients and energy of Pacific salmon carcasses to the ecosystem. Post spawning mortality of these adult fish introduces nutrients back into the stream in proportion to the number of carcasses deposited. Blockage of this allochthonous organic material from the sea can severely restrict subsequent recruitment of young salmonids in these rivers, directly by limiting their consumption of flesh from dead adults, and indirectly by reducing primary production of plankton and secondary production of benthic macroinvertebrates (Piorkowski, 1995).

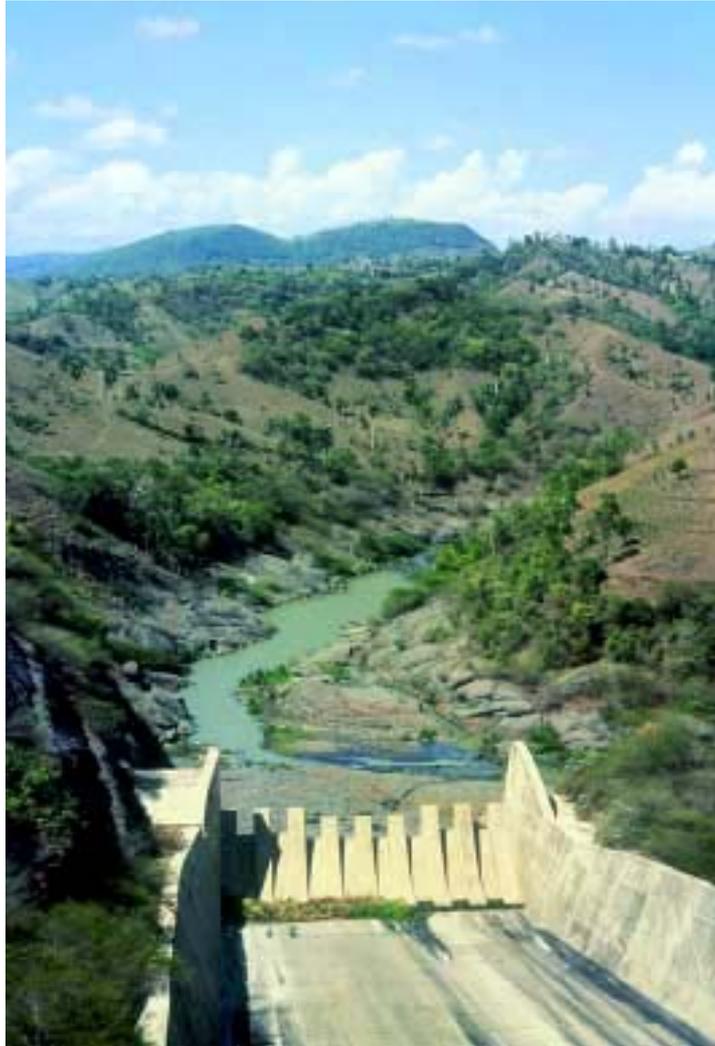


Photo 3: A dewatered stream reach downstream of a dam in the Dominican Republic. (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

Dams also can enhance some riverine fisheries, and particularly with respect to tailwater fisheries immediately below dams. Fishes can become concentrated below dams as a result of the attractive foraging opportunities there as well as from seasonal congregations of migratory fishes (Jackson, 1985a). On a per unit area basis, tailwater fisheries can be better than those of the reservoirs themselves (Bennett, 1970). Fry (1965) reported that the tailwater fisheries below Table Rock and Taneycomo dams on the White River (Missouri, USA) and Clearwater Dam on the Black River (Missouri, USA) received 7, 10 and 16 times, respectively, more fishing effort per unit area (angler hours per hectare per year) than their associated upstream reservoir. Table Rock tailwater is a coldwater tailwater dependant on stocking of exotic rainbow trout (*Oncorhynchus mykiss*), a species that does not reproduce naturally in the system. The other two tailwaters are warmwater tailwaters with native species that reproduce naturally in the rivers. Yields were 339 kg/ha, 364 kg/ha and 753 kg/ha, respectively for the Table Rock, Taneycomo and Clearwater tailwaters. Reservoir yields during the same period (1950s-1960s) for these reservoirs were: Table Rock, 21.4 kg/ha (SE 4.23, N = 10 years); Taneycomo, 71.2 kg/ha (SE 9.93, N = 9 years); Clearwater, 31.35 kg/ha (SE 8.58, N = 4 years) (Turner and Cornelius 1989). For the two warmwater systems (Taneycomo and Clearwater), the tailwaters (Taneycomo 129.5 ha; Clearwater 32.4 ha) also provided greater overall total harvests by weight than did their respective reservoirs (Taneycomo 570.6 ha; Clearwater 805 ha) (Fry, 1965). This high level of production can be related to the transport of seston (primarily plankton) from the upstream reservoir to the receiving tailwater (Jackson *et al.*, 1991).



Photo 4: A blue catfish captured in the tailwater of Coosa River below Jordan Dam (Alabama, USA). (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

Fisheries benefits from most tailwater fisheries typically encompass relatively short sections of streams below their respective dams. For example, in navigation channels of the Tennessee-Tombigbee Waterway (Mississippi, USA), tailwater influences extend approximately 4 km below Aberdeen and Columbus dams (Jackson and Dillard, 1993). In the Coosa River tailwater below Jordan Dam (a hydropeaking facility in Alabama, USA), tailwater influences on the fisheries extended approximately 4 km downstream under low flow regimes and nearly 15 km downstream under high flow regimes (Jackson and Davies, 1988a, 1988b; Jackson *et al.*, 1991). Maintaining instream flows to address fisheries concerns in the tailwater below Jordan Dam has been a subject of intense debate in the biopolitical arena of re-licensing this hydroelectric facility (Jackson, 1985a). Two examples of tailwater fisheries in Africa are the ones on the Volta River below the Akosombo Dam (Ghana) and below the Kainji Reservoir (Nigeria).

Eschmeyer and Miller (1949) and Miller and Chance (1954) estimated that 35% of the angling in Tennessee Valley Authority waters (USA) occurred below dams, and that tailwater fisheries accounted for 52% of the total harvest. Jackson (1985a), Jackson and Davies (1988b), and Jackson and Dillard (1993) recorded highly productive fisheries in the warmwater tailwaters of the Alabama-Coosa and Tennessee-Tombigbee Waterway systems in the southeastern USA. Hess *et al.* (1982) noted that reservoirs on the Missouri River produced plankton that upon discharge through the dams was beneficial to the respective downstream fisheries. However, Jackson (1985a), Jackson *et al.* (1991) and Sarnita (1991) demonstrated that plankton transport in a tailwater is rapidly attenuated downstream.

Maintaining higher discharges from dams can extend the beneficial influences of plankton discharged from the dam to lower stream reaches; and thereby lengthen tailwater fisheries in the respective system. Caution, however, is warranted, because excess flushing rates from the upstream reservoir can result in reduced residence time for water in the reservoir, which in turn can preclude development and production potentials for plankton in the reservoir. This would undermine the plankton foundation that supports both the reservoir fishery and its respective downstream tailwater.

Temperature can greatly influence riverine fishes, and particularly warmwater fishes. Ye (1996) and Jackson and Ye (2000) related hydrological and climatological factors to principal fish stocks of the Yalobusha River (Yazoo River ecosystem, Mississippi, USA) and identified water temperature ($R^2 = 0.99$) as the most important factor influencing stock structure of channel catfish (*Ictalurus punctatus*). Cooler water apparently curtailed reproduction and subsequent recruitment, and resulted in stocks dominated by larger fish. Rutherford *et al.* (1995) reported that growth increments of channel catfish in the lower Mississippi River were positively related only to length of the growing season (number of days $> 15^\circ\text{C}$) and attributed this to favourable production of fish food items (primarily invertebrates) during extended warm environmental conditions. Subsequently, cool and cold water releases from dams can curtail or eliminate warmwater fisheries in the tailwaters below the dams (Pasch *et al.*, 1980). However, oxygenated hypolimnetic discharges of cold water can sustain stocks of salmonids where normally waters are too warm during the summer for these fishes (Cadwallader, 1978). Unlike warmwater tailwater fisheries, many coldwater tailwater fisheries require supplemental stocking for their maintenance, primarily because variable flow regimes from hydropower facilities preclude availability of seasonally-stable spawning environments.

Dams purposefully or inadvertently alter downstream hydrology, including flooding. If the altered hydrology curtails or eliminates normal, historical downstream flooding, overall fisheries productivity throughout the system can be impacted negatively (Holcik and Bastl, 1977; Welcomme, 1976, 1985; 1986; Junk *et al.*, 1989). In both tropical and temperate rivers, fish yields per unit surface area are considerably greater in rivers with flood pulses and floodplains than in nearby impoundments where flood pulses are reduced or absent (Sparks, 1995). Flooding sets into motion incorporation of extra-channel allochthonous organic material as well as nutrients of terrestrial origin into aquatic dimensions of the riverine ecosystem (Vannote *et al.*, 1980; Junk *et al.*, 1989; Bayley, 1989; 1995; Thorp and Delong, 1994; Sparks, 1995).

Once flooding occurs, invertebrates and fishes colonize the inundated areas to take advantage of these allochthonous resources and their products (e.g. invertebrates) on the floodplain (Flotemersch, 1996). Floodplains thus serve as important spawning and nursery grounds, as well as important sources of food for fish of all sizes. The moving interface between the aquatic and terrestrial dimensions of the ecosystem is particularly important because this environment, which is limited in time, promotes faunal interactions biotically as well as abiotically, and rapid nutrient exchanges (Goulding, 1980; Bayley, 1989). Fish yields from floodplain river ecosystems are directly related to the height and duration of floods (Holcik and Bastl, 1977; Goulding, 1980; Welcomme, 1985; Jackson and Ye, 2000; Jackson, in press).

It is essential that a fishery be understood as a composite of three interactive components: (i) fish stocks; (ii) habitat; and (iii) people (Nielsen, 1993). If one of these components is missing, there is no fishery. The presence of fisheries resources (e.g. a reservoir stocked with fish appropriate for exploitation) does not necessarily mean that a fishery exists. People must be exploiting the resources consumptively or otherwise for there to be a fishery. This exploitation can be curtailed or rendered void or non-existent by factors such as access, culture and tradition, social disturbance, and economics. Modifications to or loss of the natural river environment supporting fish stocks, and human interactions with these stocks, can challenge or eliminate traditional, and culturally-important fisheries (Jackson, 1991). River fisheries are non-portable. Persons with individual, community and/or sub-cultural identities linked to river fisheries can suffer profound social and economic stress if the foundation for their identities (i.e., the river and its resources) is taken from them (Baird, 1994; Brown *et al.*, 1996). Shifting focus and techniques from those appropriate for the seasonal dynamics of river



Photos 5a and 5b: Tibbie Creek, a tributary of Tombigbee River (Mississippi, USA), during (a) the dry season and (b) the wet season. Both photos show exactly the same location. (Photos: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

ecosystems to those appropriate for reservoirs and tailwaters can require training and experience. However, both the training and the gain in experience require time elements that persons living and working on the social, economic and nutritional margins of a given society may have difficulties in coping with. This does not exclude that in some areas fishers can adapt readily to the new situation, as seems to be the case for Lake Volta in Ghana (Petr; pers. comm.). Elsewhere in Africa (e.g. on the reservoir Nyumbaya-Mungu in Tanzania), skilled fishers have immigrated from other countries to exploit new resources; however, this is yet another strategy and does not contradict the above statement on training needs of the local population to cope with the new conditions.



Photo 6: A good catch of river catfish, the production of which is the result of the healthy and intact floodplain river ecosystem of the Kapuas River (Kalimantan, Indonesia). (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

2. YIELD MODELS

From a global perspective, large river ecosystems are the critical lotic resources with respect to fisheries (see Dodge, 1989, and references therein). Welcomme (1985) developed yield models for large rivers relating river basin area and length of the main channel to catches.

For river basin area the relationship is:

$$C = 0.03A^{0.97} \quad (r = 0.91)$$

where C = annual yield in tons, and A = river basin area in km².

For length of the main channel, the relationship is:

$$C = 0.0032L^{1.98} \quad (r = 0.90)$$

where C = annual yield in tons, and A = channel length in km.



Photo 7: Due to the fact that there are no dams, the Pahang River (Malaysia) still has an intact floodplain river ecosystem and a productive fishery. (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)



Photo 8: Fishing for giant catfish in the Mekong River shared by Thailand and Laos. (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

Figure 1 depicts yield estimates for different channel lengths from a hypothetical large river. Exponential increases in yield as segments lengthen relate to the connectivity and cumulative influences of upstream processes within the system (“River Continuum Concept”: Vannote *et al.*, 1980), and lateral processes associated with riparian, watershed and floodplain dimensions of the stream ecosystem (“Flood Pulse Concept”: Junk *et al.*, 1989).

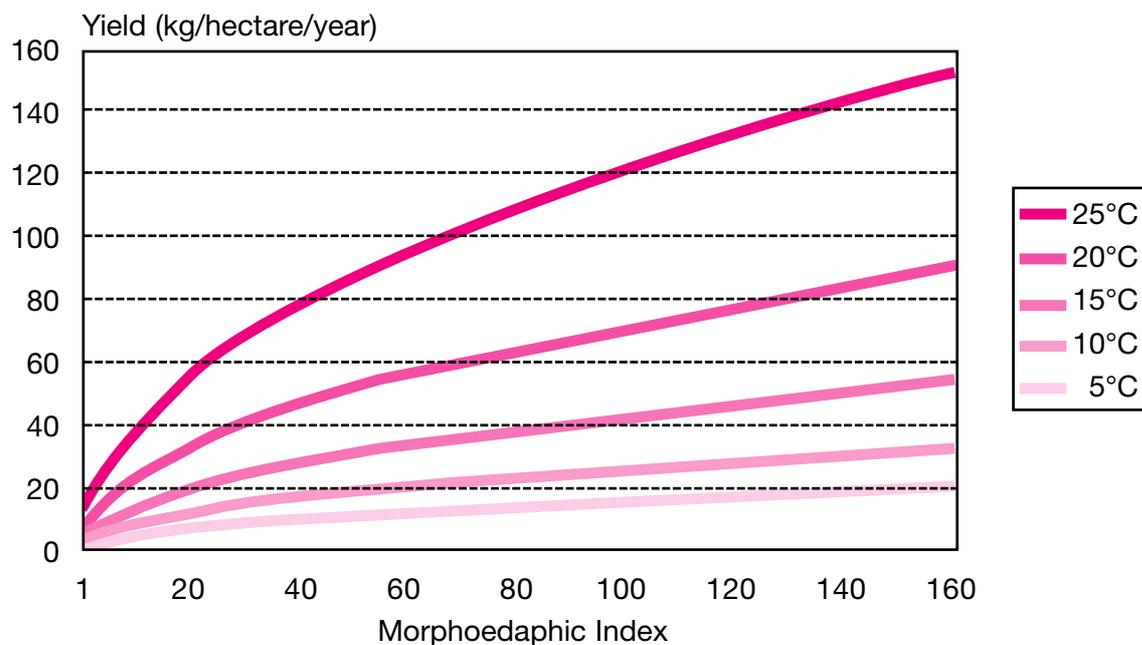


Figure 1. Predicted fish yields for reservoirs from the global yield model developed by Schlesinger and Regier (1982): $\text{Log}_{10} \text{Yield} = 0.044 \text{ Temperature} + 0.482 \text{ Log}_{10} \text{MEI} + 0.021$

With respect to lacustrine systems, Ryder (1965) developed the morpho-edaphic index (MEI) to assist in making first order estimates of fish yield from moderately fished north-temperate lakes. The MEI is calculated by dividing the value of total dissolved solids (mg/l) by the mean depth (m) of the water body. Jenkins (1982) successfully applied this methodology to North American reservoirs. However, Jenkins (1982) tracked reservoir fishery yield over time and noted substantial within-system variability in yield. This variance should be included as a characteristic of a given fishery alongside its respective magnitude parameter (i.e. mean yield). Models addressing variation in yield have not received the attention enjoyed by those addressing means.

The simplicity of the MEI, and its generally good predictive capabilities have resulted in its application worldwide, subject to regional modifications. Generally, the MEI demonstrates that as nutrients in the water increase and depth decreases, fish production increases. Jenkins (1982) emphasized that relationships can be curvilinear, with greatest predictability within intermediate ranges for MEI and less fit at extremes. Schlesinger and Regier (1982) expanded the model to incorporate temperature effects, and subsequently enhanced its global applicability. Figure 2 depicts theoretical MEI yield estimates for lakes having annual mean temperatures ranging from 5°C to 25°C using the model developed by Schlesinger and Regier (1982). Table 1 estimates fish yield for hypothetical reservoirs having surface areas of 100 to 10 000 ha, depths of 5-15 m, total dissolved solid (TDS) concentrations of 50 to 200 mg/l, and temperatures of 5°C, 10°C and 25°C.

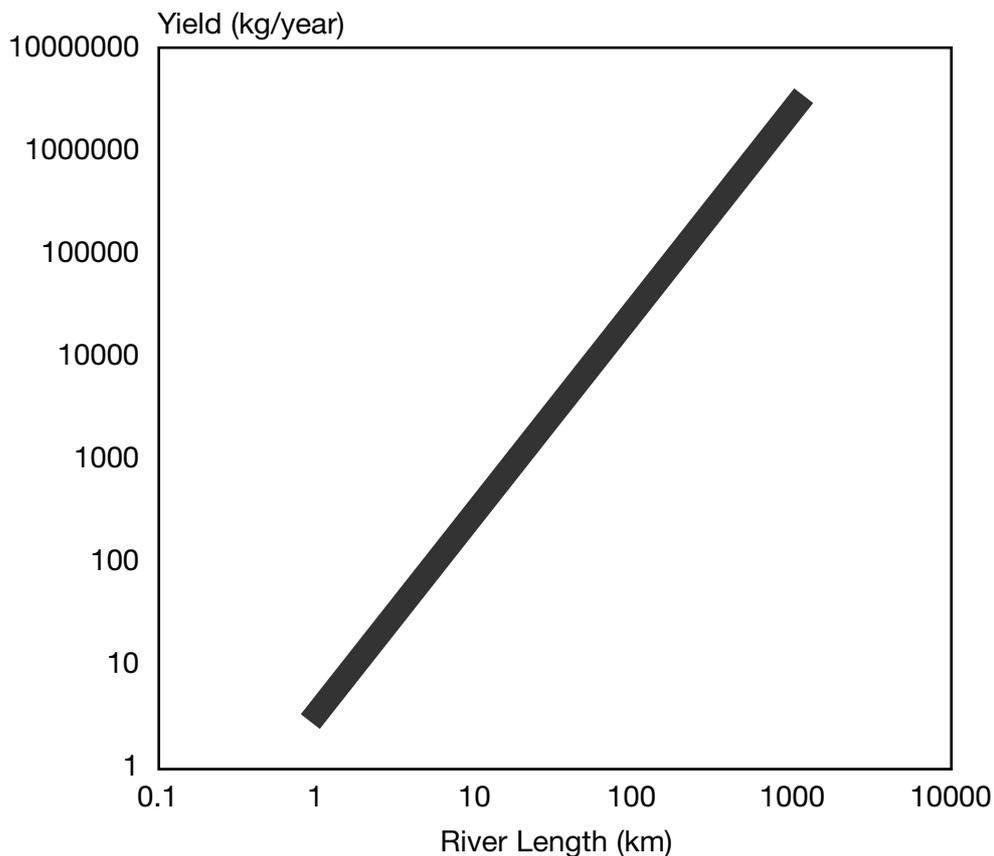


Figure 2. Predicted fish yields for rivers of different lengths (values calculated from Welcomme 1985: $C = 3.2L^{1.98}$, where C = yield (kg/year) and L = length of river (km)).

Table 1. Theoretical fish yield estimates for reservoirs having different surface areas (hectares), average depths (m), total dissolved solids (TDS, mg/l) and average annual temperatures (°C), based on the global, temperature-adapted morpho-edaphic index by Schlesinger and Regier (1982)¹.

		Annual Production (kg/year)											
		Yield (kg/ha/year)			100 hectares			1 000 hectares			10 000 hectares		
TDS	Depth	5°C	10°C	25°C	5°C	10°C	25°C	5°C	10°C	25°C	5°C	10°C	25°C
50	5	5.28	8.77	40.09	528	877	4 009	5 280	8 770	40 090	52 800	87 700	400 900
	10	3.78	6.28	28.70	378	628	2 870	3 780	6 280	28 700	37 800	62 800	287 000
	15	3.10	5.14	23.49	310	514	2 349	3 100	5 140	23 490	31 000	51 400	234 900
100	5	7.38	12.25	55.99	738	1 225	5 599	7 380	12 250	55 990	73 800	122 500	559 900
	10	5.28	8.77	40.09	528	877	4 009	5 280	8 770	40 090	52 800	87 700	400 900
	15	4.33	7.18	32.81	433	718	3 281	4 330	7 180	32 810	43 300	71 800	328 100
200	5	10.31	17.11	78.20	1 031	1 711	7 820	10 310	17 110	78 200	103 100	171 100	782 000
	10	7.38	12.25	55.99	738	1 225	5 599	7 380	12 250	55 990	73 800	122 500	559 900
	15	6.06	10.06	46.00	606	1 006	4 600	6 060	10 060	46 000	60 600	100 600	460 000

$$^1\text{Log}_{10} \text{Yield} = 0.044 \text{ Temperature} + 0.482 \text{ Log}_{10} \text{MEI} + 0.021$$

From Figure 1 and Table 1 note that if 25 km of river channel is converted to reservoir environment, an estimated 1875.5 kg/year of fish yield is lost from the river. This loss is theoretically compensated by a 100-ha reservoir in the tropics (annual temperature 25°C), regardless of depth (range 5-15 m) or TDS concentration (range 50-200 mg/l), but not by reservoirs of similar size, depth or TDS concentration in temperate (10°C) and higher latitude (5°C) regions. If the reservoir has 1 000 or more hectares of surface area associated with the 25 km of river channel, then compensation occurs throughout the entire ranges of TDS and mean depths in all the regions. Similar exercises can be conducted for longer sections of river channel and for reservoirs having greater surface area. For example, loss of fish yield from 100 km of river channel (29 184 kg/year) can be compensated by a tropical reservoir with 1 000 ha of surface area, and mean depth of 5 m with TDS of 50 mg/l, and by deeper tropical reservoirs with higher TDS concentrations; but larger reservoirs are required in temperate and higher latitude regions to compensate for the loss.

From this simple exercise, it would appear that, at least theoretically and hypothetically, reservoir fisheries can reasonably mitigate losses sustained from impacts to river fisheries. However, a potential, fundamental weakness in the comparison is that the river model does not have the same temperature adjustment factors as does the reservoir model. Additionally, the actual size (width; depth) and gradient

of the river may have some bearing on yield, not only in terms of biological production, but also with respect to exploitation by persons engaged with the fishery. Finally, there can be cumulative (positive) influences on the fishery as one proceeds from headwaters to downstream reaches of the river (e.g. higher nutrient loads; substrates with higher organic content; greater diversity in terms of size and content of allochthonous organic material inputs; more stable thermal regimes) (Vannote *et al.*, 1980).

In this last regard, consider again the 25-km segment of river utilized for the exercise above. The general model estimates that fishery yield for a 25-km segment is 1 875.5 kg/year. However, considering cumulative influences upstream to downstream (Table 2) and using the model developed by Welcomme (1985, p. 213), we note that at a distance of 50 km from the river's source, a 25-km section of river yields 9 113 kg/year and at a distance of 250 km downstream from the source, a 25-km section of the river yields 37 197 kg/year. If a dam were constructed at a distance of 400 km from the river's source, and resulted in loss of a 25-km section of the river at that point, the reservoir would need to compensate for 57 925 kg/year. This could be accomplished, for example, with tropical reservoirs having mean depth of 5 m, TDS of 100 mg/l and a surface area of somewhat more than 1 000 ha. Temperate reservoirs with the same mean depth and TDS could compensate for this loss of river fishery yield with a surface area of 4 728 ha. Although the distance compensating model for this exercise was developed for African rivers, it has been used successfully for rivers in other regions (e.g. the Mekong, Danube and Magdalena rivers) (Welcomme, 1985).

Table 2. Estimated fish yields for a 25-km section of river at different distances from the river's source along the river continuum.¹

Distance From Source (km)	Catch (kg/year)
50	9 113
100	16 213
150	23 248
200	30 239
250	37 197
300	44 127
350	51 036
400	57 925
450	64 798
500	71 657

¹ Calculated from the model developed by Welcomme (1985, p.213): ${}_x C_y = C_{x+y} - C_y$ where x = the length of the stream segment (25 km in the example), y = the distance of the stream segment from the river's source and C = yield in kg/year. Catches for C_{x+y} and C_y are calculated by the equation $C = 3.2 L^{1.98}$, where L values are lengths for x + y and y, respectively.

Much depends on the specific nature of the riverine fishery in question. If the riverine fishery is sustained by stocks of migrating fishes that become blocked by a dam, the riverine fishery can be severely impacted. If the migrating fishes are anadromous or catadromous species, linked to ocean fisheries, or those of inland seas or large lakes, the negative impacts to these stocks and their associated fisheries can be catastrophic. Carried to the extreme, stock reductions can reach levels where the stocks become threatened beyond fishery concerns (i.e. no longer economically feasible to exploit), and enter the arena of bio-ethical concerns regarding their extirpation from this planet (see Cederholm *et al.*, 1999).

Unfortunately, there really is no simple formula for addressing the impact of dams (positively or negatively) on riverine fisheries. There are, obviously, situations where reservoir fisheries are great assets. For example, Sugunan (1997) reviewed fisheries in small impoundments for seven countries

representing Africa, Asia and Latin America/Caribbean. He reported that tilapia (exotic fishes), especially in island nations (e.g. Cuba and Sri Lanka) increased fish production in reservoirs. This is particularly important in countries such as these where contributions by river fisheries to overall national fishery yields are naturally relatively minor. Success with regard to enhancing fish yield via reservoir fisheries also was noted for situations where there were few competing species, and few predators. Even in countries with substantial river fisheries, reservoir fisheries development has been beneficial. For example, Sugunan (1997) noted that tilapia stocked into small Brazilian reservoirs in the northeast region of the country resulted in higher fish yields than those from reservoirs without tilapia. Reservoir construction in drier zones of India, Thailand, northeast Brazil, Sri Lanka and Mexico is primarily for agriculture irrigation, but these reservoirs provide secondary benefits via fisheries. Yields from small impoundments located in the seven countries addressed by Sugunan (1997) averaged 165 ± 16.3 kg/ha/year.

Marshall and Maes (1994) compared yields from various types of water bodies in the tropics (Table 3). Shallow, managed, reservoirs averaged 30-150 kg/ha/year; deep reservoirs averaged 10-50 kg/ha/year; floodplains averaged 200-2 000 kg/ha/year; and large, slow-flowing rivers averaged 30-100 kg/ha/year. From these data, it seems that fisheries in large rivers hold their own quite well with respect to yield when compared to those of reservoir fisheries. Additionally, and if floodplains are included as components of the river (which they are), then reservoir fisheries, even in the tropics where they are most productive, are far less productive than river fisheries on a per unit area basis. Permanently inundating a floodplain by an impoundment (thereby restricting the moving littoral zone, *sensu* Bayley, 1989; Junk *et al.*, 1989), or regulating water release from dams so that downstream floodplains are not sufficiently inundated in terms of depth, duration and seasonality of flooding, can potentially result in significant overall fishery losses.

Table 3. Estimated annual fish productivity from diverse aquatic systems in the tropics (compiled by Marshall and Maes 1994).

Type of water body	Annual productivity (kg/ha)
Fish Culture Ponds	400 - 9,300
Floodplains	200 - 2,000
Shallow natural ponds	50 - 1,000
Shallow lakes	50 - 200
Shallow managed reservoirs	30 - 150
(perennial)	110 - 300
(seasonal)	up to 200
Large, slow-flowing rivers	30 - 100
Deep lakes	10 - 100
Deep reservoirs	10 - 50
Small rivers and streams	5 - 20
Swamps	5

Table 4 provides yield data from selected reservoirs worldwide. Although there is considerable variance in this data, the general trend seems to be that tropical and subtropical reservoirs tend to be more productive than temperate reservoirs with similar morphoedaphic characteristics. Additionally, smaller reservoirs are generally more productive on a per unit area basis than are larger reservoirs. Smaller impoundments usually have greater surface area to volume ratios than do larger impoundments. As a result, smaller impoundments tend to have overall higher primary production than do larger impoundments. Higher primary production typically enhances fishery yields. However, these size-related benefits can be lost if the impoundment is subject to excessive flushing or desiccation.

Table 4. Fish yield from selected reservoirs worldwide.

Region	Yield (kg/ha/year)	Reference
Africa:		
Small Reservoirs	329	Marshall & Maes (1994)
Medium Reservoirs	80 - 90	Kapetsky (1986); van der Knapp (1994)
Large Reservoirs	27 - 65	Kapetsky (1986); Machena (1995);
		Rashid (1995); Braimah (1995)
Asia:		
China	127 - 152	Lu (1986)
India		
Small Reservoirs	49.5	Sugunan (1995)
Medium Reservoirs	12.3	Sugunan (1995)
Large Reservoirs	11.4	Sugunan (1995)
Kazakhstan	15	Petr & Mitrofanov (1998)
Malaysia	3 - 12	Ali & Lee (1995); Ali (1996)
Sri Lanka	40 - 650	Sugunan (1997)
Latin America & Caribbean:		
Brazil	2.1 - 11.5	Dos Santos & de Oliveira (1999)
		Sugunan (1997)
Cuba	125	Sugunan (1997)
Dominican Republic	29 - 75	Jackson (1985)
Panama		
Gatun Lake (Panama Canal)	4.8 - 5.3	Bayley (1986); Maturell & Bravo (1994)
Bayano Lake	63.2	Candanedo & D'Croz (1983)
North America & Europe:		
Austria (Danube system)	32	Bacalbasa-Dobrovici (1989)
Commonwealth of Independent States	0.1 - 48.1	Karpova <i>et al.</i> (1996)
Germany		
Danube system	65 - 76	Bacalbasa-Dobrovici (1989)
Rhine system	21 - 62	Lelek (1989)
Poland (Vistula system)	26	Backiel & Penczak (1989)
United States	24	Jenkins (1982)

The variation noted above suggests that partitioning the world into general regions may clarify relationships between dams and reservoirs and their respective river fisheries. For partitioning purposes the following regions were delineated: Africa, Asia, Australia, Latin America and the Caribbean, North America, Europe and the Commonwealth of Independent States.

3. REGIONAL ASSESSMENTS

3.1 Africa

Welcomme (1985) estimated that yield potentials from African river and floodplain fisheries ranged from 5 to 143 kg/ha/year. Actual yields in large reservoirs subject to moderate to heavy fishing varied from 27 to 65 kg/ha/year (Kapetsky, 1986). For medium-sized reservoirs, mean yield estimated from actual yield values provided by van der Knapp (1994) was approximately 80 kg/ha/year. Mean yield from a variety of Sub-Saharan small water bodies was 329 kg/ha/year (Marshall and Maes, 1994).

Petr (1975) addressed factors associated with initial high fish catches in African reservoirs. High fish catches were related mainly to annual formation of floodplains during the gradual rising of waters over several years, and the formation of aufwuchs (periphyton) on submerged terrestrial vegetation. Peak landings occurred in 5-6 years (Kariba; Volta), and coincided with the year when water levels reached maximum pool level. By this time, the main lake commercial fish stocks were completely different from that of the original river (catches dominated by tilapia). In faster filling lakes with rapid drawdowns (e.g. Kainji) commercial fish landings peaked the first year. Rapid drawdowns restricted spawning by tilapia and reduced their expansion throughout the system. In Lake Kariba, *Limnothrissa miodon*, an introduced species from Lake Tanganyika, is now an important component of fish landings. Without this fish, catches would be only around 3 000 t (T. Petr, pers.comm.).

In the Kafue River reservoir above Kafue Gorge Dam (Zambia), the large surface area and shallow water of the reservoir benefitted tilapia species that form a major part of the commercial catch (Dudley, 1974). Water level fluctuations can be advantageous to impoundment fisheries (particularly those with expansive shallow-water zones), as well as river floodplain fisheries in the region, because alternating wet and dry conditions reverse nutrient losses through oxidation and leaching. Drought-induced loss of fish stocks in small impoundments can be addressed through restocking once the systems refill (Mheen, 1994), assuming that restocking is economically feasible and that fish for restocking are available.

Dams have reduced overall fishery yield from some African systems. Such yield reductions can be temporary or long term. For example, Lelek and El-Zarka (1973) reported that two years after filling Lake Kainji, fish catches from the system were reduced by 30%. Post impoundment studies of the system suggested that the commercially important Mormyridae were reduced from about 20% of the catch to around 5% (Lelek and El-Zarka 1973; Lewis 1974). Catches tended to increase to pre-impoundment levels as the system stabilized.

Sagua (1997) addressed Lake de Guiers, a natural lake in Senegal. The lake in its natural condition was fed by the Senegal River during floods and dried during drought. A dam was constructed to divert more water into the lake. Fish production in the lake increased from 2 500 t/year to 3 000 t/year. Prior to the drought, fish production in the river and its floodplain was 23 500 t/year. Although the dam controlled flooding, it reduced the river fishery by 50%, and shifted stocks toward marine fishes due to intrusion of saline waters. There was an annual net loss of 11 250 t of fish from the system.

Crul and Roest (1995) compiled fisheries assessments for Africa's four largest reservoirs: Kainji, Kariba, Nasser/Nubia, and Volta. Considered collectively using minimum and maximum yield estimates from each system, average yield for these four reservoirs is 28-38 kg/ha/year. System-specific assessment summaries are provided below.

Lake Kainji

Balogun and Ibeun (1995) addressed fisheries of Lake Kainji. Catches fluctuated between 4 500 and 6 000 t/year which translates to production values of 3.5-4.7 kg/ha/year. The Niger River pre-

impoundment sustained fisheries composed primarily of mormyrids, citharinids and distichodontids. During the first two years post-impoundment, the “false flood” in the newly-formed Lake Kainji stimulated production of these floodplain river fishery resources, particularly for citharinids and distichodontids, but thereafter production of these fishes decreased. Mormyrids never did well post-impoundment. In contrast, catches of cichlids, cyprinids and bagrids were low pre-impoundment but after impoundment significantly increased. Littoral zones of the lake were most productive.

Lake Kariba

Machena (1995) addressed the fisheries of Lake Kariba (Zambia/Zimbabwe). Yields were 60 kg/ha/year for pelagic fishes (e.g. the sardine *Limnothrissa miodon*). When the inshore fisheries are included, yields were 30-57 kg/ha/year.

Lake Kariba is considered an oligotrophic system with low fish production potential (limited by nitrogen and phosphorus). Most fish production is in shallow littoral areas but most of the reservoir has steeply sloping shoreline. Within the inshore areas, crocodiles consume the equivalent of 10% of the catch. Catch composition is shifting toward benthic fishes, especially catfishes (e.g. *Synodontis zambezensis*). In 1989 there were nearly 2 000 artisanal fishers in Zimbabwe and nearly 1 000 in Zambia. Most fishers (91%) in Zimbabwe were full time and fished with 2-3 gillnets. The fishery was plagued by high catch spoilage and low productivity. Comparable fishery characterization data for Zambia were unavailable.

Lake Nasser/Nubia (Egypt and Sudan)

Rashid (1995) addressed these fisheries and estimated yield at 36-39 kg/ha/year. Tilapia (*T. nilotica* and *T. galilaea*) contribute 89% to total landings. In Egypt, the impoundment of the Nile River by the Aswan High Dam (1964) to create Lake Nasser/Nubia led to increased fish yields in the impounded section of the river, but due to trapping of nutrients in the impoundment that led to this productivity, there were declines in the pelagic fisheries in the entire eastern Mediterranean Sea (Ryder 1978). After construction of the Aswan High Dam, Bernacsek (1984) estimated fish yield in the lower Nile River at 72.75 kg/ha/year.

Lake Volta

Braimah (1995) addressed fisheries of Lake Volta. Estimated yield was 42-52 kg/ha/year based on catch statistics, and 12 kg/ha/year based on the morphedaphic index, MEI, (Ryder *et al.*, 1974). Tilapia are a major component of the harvest, with catches influenced by water level (higher catches when water level is low).

During reservoir drawdowns, standing timber is harvested for firewood and to facilitate beach seining. However, standing timber in the reservoir basin is important for periphyton production. Braimah (1995) estimated that 52% of the fish caught were dependant on invertebrates exploiting this periphyton. Removal of standing timber, in conjunction with overfishing, has negatively impacted the fish stocks.

3.2 Asia

3.2.1 Southeast Asia

Fish migration is a primary concern throughout this region. Kvernevik (1997) concluded that fishes in Malaysian rivers utilized migration as an important adaptive tactic, and that migratory species were more common in the Kelantan River system, which has no large hydroelectric dams acting as barriers, than in

the Perak River where there are four large hydroelectric dams acting as mainstream barriers. Roberts (1995) discussed impacts from 12 hydropower projects on the mainstream of the Mekong River and stressed that the combined impact on fisheries from these dams is greater than the sum of the individual impacts. Each of the Mekong River dams addressed by Roberts (1995) will block fish migrations.

Dams, however, are not the only concerns with respect to riverine fisheries in the region. For example, Roberts (1993a) attributed the 80-90% declines in fisheries below the great waterfalls of the Mekong River (southern Laos) primarily to overfishing and to fishing with explosives. Roberts (1993b) emphasized that tropical rivers in regions subject to deforestation and dams become increasingly simplified ecologically and unable to withstand additional impacts. Following construction of the Pak Mun Dam (Thailand) Roberts (1993b) emphasized the need to consider industrial development associated with the dam, and its impacts to river fisheries. He also expressed concern that 200 fish species occurring naturally in the river would be replaced with only 25 species stocked from hatcheries into the reservoir above the dam.

In Malaysia, there are 51 impoundments (46 in Peninsular Malaysia, 3 in Sabah, 2 in Sarawak) ranging in size from 10 ha (Mahang Dam) to 37 000 ha (Kenyir Dam) (Ho 1995) and 94 major river systems (49 in Peninsular Malaysia, 24 in Sabah, 21 in Sarawak)(Yap 1992). Yap (1992) reported yields for four principal rivers: Rajang (Sarawak, 100 kg/ha/year); Baram (Sarawak, 142-169 kg/ha/year; Gombak (Selangor, 180 kg/ha/year), Perak (Perak, 11.64 kg/ha/year). Khoo *et al.* (1987) reported that inland capture fisheries in Malaysia are dominated by cyprinids and silurids in the country's larger river systems, and that there have been sharp declines in catches during recent decades. These declines are attributable to a combination of factors, including river regulation (particularly dewatering of stream reaches below dams), (D. C. Jackson, Mississippi State University, pers. observ. 1978-1980, and 1997, 1998, 1999) and pollution, siltation, damming, illegal gear/methods, and overfishing (Khoo



Photo 9: The Temenggor Reservoir (Malaysia), which shows extreme drawdowns and exposure of steep littoral zones, doesn't have a good fisheries production. (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)



Photo 10: Sport fishing in an upper reach of a Pahang River tributary (Malaysia). (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

et al 1987). In the Selangor River, flows have been reduced from 5 482 000 m³/day to 300 000 m³/day and in Sabah, the release from the Babagon Reservoir dam has reduced streamflow to 5.5-21.0% of the natural river flow (Yap 1992).

Reservoir systems along the Perak River in Malaysia have received considerable attention with respect to fisheries research. Along the Perak River, evaporation from the reservoirs may exceed streamflow. The result can be dewatering of the tailwaters and loss of riverine fish habitat (D.C. Jackson, Mississippi State University, U.S.A., pers. observ. 1978-1980, and 1997, 1998, 1999). Khoo *et al.* (1987) reported that Chenderoh Dam blocked movements of *Probarbus julieni* and reduced breeding and spawning grounds. Ali (1996) reported higher biodiversity in the Chenderoh Reservoir than in the river downstream from the dam but diversity in the reservoir has declined over time and fish standing stock is low. Yield from the reservoir fishery was estimated at 12.2 kg/ha/year which, while low, exceeded that of Bukit Merah Reservoir, a blackwater reservoir in the same region (3.7 kg/ha/year) (Ali and Lee, 1995). Limnological studies of impoundments along Malaysia's Perak River indicate that standing crop of phytoplankton and zooplankton is minimal, species are characteristic of oligotrophic fauna and production generally is low except for a brief period during the dry season (A.B. Ali, Universiti Sains Malaysia, Penang, pers. comm., 1999). Deep water reservoirs in Malaysia that have low retention times, and that are designed primarily for hydroelectric purposes, may have limited fishery potentials.

In Malaysian streams that have not been dammed (e.g. Tembling River, Pahang River system), demands for river fish have resulted in overfishing (Tan and Hamza, Universiti Sains, Penang, Malaysia: undated publication). Semi-sanctuary status provided to the upper Tembling River and its principal tributaries as a result of being in the National Park (Taman Negara) has protected fish stocks somewhat, primarily for recreational fisheries and to support demands for fish by tourist restaurants near the national park headquarters (D.C. Jackson, Mississippi State University, USA, pers. observ.,

1997; 1999). Elsewhere in interior Malaysia, pollution and sedimentation impact riverine fisheries, especially during the rainy season when runoff is increased (Ho, 1995).

Lake Kenyir, the largest reservoir in Malaysia, has a surface area of approximately 36 000 ha, a maximum depth of 145 m, and a mean depth of 37 m (Yusoff *et al.*, 1995). The lake sustains a small-scale commercial fishery as well as popular recreational fisheries, with yields estimated at approximately 20 kg/ha/year (Yusoff *et al.*, 1995). These overall low yields are the result of an anoxic hypolimnion, lack of forage in the pelagic zone and few lacustrine fish species (Yusoff *et al.*, 1995). Historical fish migrations in the river were blocked by the dam which does not have a fish ladder (Yusoff *et al.*, 1995).

Sukadi and Kartamihardja (1995) described fisheries associated with reservoirs in Indonesia. There are 23 major reservoirs in the country. Average yield from 13 principal reservoirs was 174.5 kg/ha/year (range 5.3 kg/ha/year - 692.9 kg/ha/year). Yield estimates for river fisheries were not provided but those of floodplain environments ranged from 100 kg/ha/year to 800 kg/ha/year.

3.2.2 Southern and Central Asia, Kazakhstan, and the Middle East

Sugunan (1997) reported that fish yields in Indian rivers range from 0.64 to 1.64 t/km (average 1.0 t/km) with 3.2-7.8 fishers/km. In the Ganga River, yields declined from 50.3 kg/ha/year (1960s), to 20.0 kg/ha/year (1972) down to 6.5 kg/ha/year (mid-1980s). Specific reasons for this decline were not documented. Based on these figures, Sugunan (1997) determined that rivers in India do not contribute significantly to the country's total inland fish production in terms of volume, although a large number of traditional, artisanal fishers exploit middle and lower stretches of the rivers.

Sugunan (1995) addressed impoundment fisheries throughout India, and estimated fish yields for 291 small (49.9 kg/ha/year), 100 medium (12.3 kg/ha/year) and 21 large (11.43 kg/ha/year) reservoirs. The overall national production rate for Indian Reservoirs was 20.1 kg/ha/year. He reported that supplemental stocking of small impoundments in India can yield on average 146 kg/ha/year (range 63-316 kg/ha/year).

Dams have had negative impact on river fisheries in various systems throughout the region. Dam construction on the Sefid River (Iran) resulted in reduced streamflow, increased water temperature and declines in food items for sturgeon (Acipenseridae) (Vladykov, 1964). Reservoirs constructed on rivers emptying into terminal lakes of Central Asia and Kazakhstan severely reduced stocks of migratory fishes in the rivers, encouraged development of stocks more lacustrine in character, exacerbated precipitation/evaporation deficit ratios and have led to accelerated salination of groundwater as well surface waters (Petr and Mitrofanov, 1998). Sandhu and Toor (1984) noted sharp declines in catches of *Hilsa ilisha* as a result of dams, barrages, weirs and anicuts on the Hoogly, Godavari, Krishna and Cauvery rivers (India), and that mahseer *Tor putitora* and *T. tor* no longer are found above Nangal and Talwara dams. Fishways constructed in conjunction with dams are used as fish traps by local fishers.

In addition to impacts on hilsa and mahseer stocks and their associated fisheries, formation of reservoirs in India has had negative impact on snow trout (*Schizothorax*), and rohu (*Labeo*) in Himalayan streams, and catadromous eels and freshwater prawns in all major river systems. One of the earliest known impacts to river fisheries in India occurred as a result of construction of Mettur Dam (1935) on the Cauvery River, which formed Stanley Reservoir and completely stopped runs of the Indian shad *Tenulosa ilisha*. Within the reservoir itself, water level changes, recruitment failures and predation resulted in reduced stocks of Indian major carps.

Sugunan (1995) noted that some fishes (e.g. the exotic tilapia, *Oreochromis mossambicus*) do well in Indian reservoirs, but that tilapia are more or less restricted to tropical regions of the country. Introduction of tilapia in many Indian reservoirs has resulted in declines in native fishes and, in systems dominated by tilapia, low overall fish yields. Stunting is a problem with tilapia (especially

O. mossambicus), and particularly so in small impoundments. In larger reservoirs, tilapia can achieve weights of 2.5 kg (average 0.5-0.7 kg) (Sugunan, 1997). For tilapia fisheries, *O. niloticus* is considered a better fish and apparently does not have the same stunting problem as *O. mossambicus*. Tilapia often enjoy high consumer preference, even when the price is the same as Indian carps (Sugunan, 1995).

Gill (1984) addressed the effect of dams on the fish fauna of India's Punjab region. Reservoirs in this region have resulted in good fisheries, with more than 1 800 t/year landed annually at Bhakra Dam and Pong Dam, collectively. However, river fisheries have been negatively impacted, particularly with regard to migratory fishes. Construction of barrages at Ropar, Harike, and Ferozepur has restricted migration of Indian major carps, in spite of fishways. During most of the year, little water is released into the river below the dams from the reservoirs, and fish are concentrated in pools where they are more easily captured by fishers. Fishways designed to promote fish passage past dams are used by fishers to capture fish.

Dams in India's Punjab region have reduced flooding, but in so doing they have also negatively impacted production of Indian major carps, resulting in reduced total fish production for the region (Sandhu and Toor 1984). However, in the reservoirs formed by these dams high yield fisheries have evolved, primarily through development of stocks of exotic fishes (e.g. the fishery for the exotic silver carp *Hypophthalmichthys melitrix* contributes more than 30% to the catch from Gobindsagar Lake) (Sandhu and Toor, 1984).

George (1995) described the fisheries of Pakistan's six Water and Power Development Authority reservoirs. The combined area of these reservoirs is 99836 ha. During the period 1979-1994, fish yields ranged from 3.8 kg/ha/year (1985-1986) to 25.6 kg/ha/year (1993-1994) with an overall average yield for the entire period of 15.2 kg/ha/year.

In Sri Lanka there are 100 rivers, of which 28 are large (basins greater than 500 km²). However, and with the exception of floodplains, which have yields of 18-284 kg/ha/year, Sugunan (1997) reported that river fisheries in Sri Lanka were insignificant. Inland fisheries contributed 20% to the country's total fish production and most of this came from exotic fishes (e.g. tilapia) in reservoirs. Average yield was 244 kg/ha/year (range 40-650 kg/ha/year) (Sugunan, 1997). The higher production in Sri Lanka compared to that of India can be related to generally shallower water and greater conductivity in Sri Lanka reservoirs, and to the many competing species as well as large predators in Indian reservoirs (Sugunan, 1997).

3.2.3 China

Lu (1986) reviewed reservoir fisheries in China. At the time of his report, total surface area of reservoirs was two million hectares. Yield from reservoirs historically has been high (127-152 kg/ha/year) but this likely reflects the results of intensive stocking programmes, primarily of carps.

There are five major rivers in China: the Heilongjiang (3 101 km); Huanghe (also known as Yellow River, 5 464 km); Huai (1 000 km); Changjiang (also known as Yangtze River, 6 300 km) and Zhujiang (also known as Pearl River, 2 210 km). Dudgeon (1995) conducted an assessment of river regulation influences on fisheries in southern China. On the Zhujiang River system (the largest south of the Changjiang River), there are 40 large reservoirs and 200 smaller reservoirs. Fish catches peaked in the 1950s (10 367 t/year).

By the early 1980s, catches had fallen to 6 463 t/year, likely as a result of a combination of factors, including the influences of dam construction and operation. For example, there have been significant declines in carp recruitment, primarily as a result of pollution and overfishing. Additionally, most of the dams were built without fishways. Construction of the Sijin Hydroelectric Station in 1958 caused a reduction in carp populations. This reduction was attributed to a combination of reduced river flow, blockage of migration routes and lowered water temperatures. Clupeids (e.g. *Macrura reevesii* and *Clupanodon thrissa*) once migrated into the upper reaches of the Dongjiang River to spawn. These spawning runs were eliminated by construction of five dams in the lower reaches of the river.

Additionally, these dams reduced the abundance of carp, especially *Cirrhinus molitorella*, to levels where there is no longer an economically viable fishery in the river.

Luo *et al.* (1992) have projected that the Three Gorges Dam project will cause the fishery of the Changjiang¹ River estuary and adjacent waters to shift to the northwest of the estuary. Additionally, and with respect to the Three Gorges Dam, there is some concern regarding the Yangtze sturgeon (*Acipenser dabryanus*) (Dudgeon 1995). No facilities are planned to facilitate upstream migration of fishes past the dam. This may, however, be a moot point because fish movements (and particularly those of migratory species) in the river were blocked in 1981 by the Changjiang Low Dam at Gezhouba (Zhong and Power, 1996). This blockage reduced populations of the Chinese sturgeon (*Acipenser sinensis*), partly through alteration of downstream flows and changes in sediment characteristics that reduced spawning success. Xin *et al.* (1991) reported that the proportion of mature Chinese sturgeon in the system after construction of Gezhouba Dam has fluctuated between 13.5 and 78.0%, and that the population has maintained a 1:1 sex ratio since interception of flows began in 1981. Subsequently, Xin *et al.* (1991) did not consider the Gezhouba Dam a threat to this species.

Below two high head dams, Xinanjiang Dam (Qiantang River) and Danjiangkou Dam (Han River), fish spawning has been delayed 20-60 days by lower water temperatures (Zhong and Power, 1996). Reduced water velocities and less variable discharges caused spawning grounds below the dams to be abandoned. Changes in the hydrological regime caused extinction of *Macrura reevesii*, a highly valued fish, in the Qiantang River. In the Qiantang River estuary, the number of freshwater fish species declined from 96 to 85, whereas marine species increased from 15 to 80. Loss of habitat eliminated torrential riverine habitat species from areas inundated by Xinanjiang and Danjiangkou reservoirs. Now lentic species dominate the reservoir fish assemblages. The expanded aquatic habitat has however, been beneficial to overall fishery production. Catches from the two reservoirs have continued to increase 20 years after impoundment, but this may be the result of supplemental stocking from fish hatcheries.

Grass carp *Ctenopharyngodon idella*, black carp *Mylopharyngodon piceus*, silver carp *Hypophthalmichthys molitrix*, and bighead carp *Aristichthys nobilis* in China are highly adaptable species (Dudgeon, 1995), and are reported to be successfully spawning in Chinese reservoirs (Liu *et al.* 1986). Their spawning grounds are widely distributed, and fishways for bypassing dams are not considered necessary to sustain the fish stocks (Yi *et al.*, 1991).

The Danjiangkou Dam on the Hanjiang River prevents movements of eels (*Anguilla japonica*) (Liu and Yu, 1992). The dam also has blocked migration of commercially-important carps. Movements now are primarily seasonal downstream from the dam. Overall, the sizes of young-of-the-year fishes have decreased, growth of herbivorous fishes has slowed, populations of planktivorous fishes are small and slow growing, and dietary shifts have been noted (e.g. grass carp now feed on attached algae rather than on vascular plants; mollusk-feeding fishes now forage primarily on mussels rather than snails). Although riverine fisheries have been negatively impacted, fisheries in the reservoirs have greatly expanded (estimated yield: 1 000-1 500 t/year).

3.3 Australia

Walker (1985) conducted assessments of principal river fisheries in Australia. In northeastern Australia, dams, weirs and tidal barrages have resulted in declining catches of barramundi (*Lates calcarifer*), a catadromous species in coastal rivers, estuaries and mud flats. In southeastern Australia, a weir on the Lerderberg River (Victoria) disadvantaged the native short-finned eel (*Anguilla australis*) and river blackfish (*Gadopsis marmoratus*) and to some extent the exotic brown trout (*Salmo trutta*), but favoured the introduced perch (*Perca fluviatilis*), carp (*Cyprinus carpio*) and tench (*Tinca tinca*). Dewatering below Tallowa Dam (Shoalhaven River, New South Wales) was destructive to downstream

¹ also known as Yangtze River

fish populations of Australian bass (*Macquaria novemaculeata*), Australian greyling (*Prototroctes maraena*) and Macquarie perch (*Macquaria australasica*). In Tasmania, dams and gauging weirs have been constructed in a way to assist fish movements, particularly for commercially important migrating eels. Fish ladders also have been installed to assist galaxiids and lampreys. In the Murray-Darling system, a diversion weir 200 km downstream from Hume Dam is a barrier to fish. Weirs and dams have resulted in replacement of the Murray crayfish (*Euastacus armatus*), a river adapted species, by its floodplain counterpart, the yabbie (*Cherax destructor*). Most native fish species have declined, including the Murray cod (*Maccullochella peeli*) and river blackfish. Disruption of seasonal flood cycles has had a negative influence on spawning and recruitment processes of some native fishes.

More recently, Walker and Thoms (1993) reviewed environmental effects of flow regulation on the lower Murray River. Historically, Murray cod and callop or golden perch (*Macquaria ambigua*) have been the two primary commercial fishery resources in the river. Since 1950, Murray cod have declined in conjunction with expansion of water storages, diversions and irrigated agriculture. The Murray River now has the lowest commercial fish yield per km² of floodplain of any of the world's major rivers, although historical catches were comparable. Additionally, there is a clear correlation between callop catch and river levels. Proliferation of weir-pool environments, increases in annual proportional flow deviation and general increases in regulation in the Murray-Darling River system, have resulted in reduced species diversity, and conditions more favourable to exotic species like common carp (Gehrke *et al.*, 1995; Walker, 1985). T. Petr (pers.comm., 2000) emphasized that if common carp were included in the commercial catch of the Murray River, yield per km² would be increased considerably.

In Queensland, reservoir stocking is conducted to enhance recreational fisheries (Petr, 1998). Ongoing release of fingerlings is necessary in Queensland reservoirs because the fisheries are primarily put-grow-and-take fisheries using species that do not reproduce in the impoundments (e.g. barramundi).

3.4 Latin America/Caribbean

3.4.1 South America

Sugunan (1997) reported that there were 68 800 impoundments in Brazil of which 50 are greater than 10 000 ha and 520 are greater than 1 000 ha. These are primarily for hydroelectric and irrigation projects. Most small reservoirs are in the northeast region of the country which is prone to drought. Agencies constructing dams must guarantee that river fauna are not affected by obstructing the river. Fish passes are required if necessary to accomplish this, or affected fishes must be propagated and stocked in the upstream areas. Additional concerns should consider loss of spawning and recruitment grounds resulting from changes in hydrology and from exacerbated sedimentation resulting from dam construction and operation. Introduced species dominate the catches (mostly *Oreochromis niloticus* and *Pescada caucunda*). More than half of the catch from northeast Brazil is tilapia. With the exception of northeast Brazil, there are strict regulations regarding stocking of exotic fishes.

Dos Santos and de Oliveira (1999) conducted reservoir fisheries assessments for a 2 360-km² reservoir located on the Uatum River 170 km upstream from Manaus (Brazil). Fish diversity has been reduced and there have been other environmental and social changes resulting from the project. However some fish species proliferated in the reservoir and have resulted in development of a reservoir fishery. Yields were very low (2.1 kg/ha/year), with the fishery primarily exploiting tucunare (*Cichla* sp.). Total annual production is estimated at 500 t/year.

Gomes and Miranda (in press) studied reasons for low fishery production in Brazilian reservoirs and concluded that climate and hydrology precluded synchronization of phytoplankton production, thereby undermining the foundation for fish production in these systems. Retention time for water in the reservoirs was considered a critical factor. Unless there was sufficient time, phytoplankton blooms conducive for supporting fisheries could not be developed and sustained.

Itaipu Dam (Parana River, Brazil) encompasses 135 000 ha and has a total catch of approximately 1 560 t/year (Sugunan, 1997). This corresponds to a yield of 11.5 kg/ha/year. Sugunan (1997) reported that prior to impoundment there were 113 fish species in the affected river reaches and that approximately 20 species have been negatively impacted by the dam. Borghetti *et al.* (1994) collected fishes from the Itaipu Dam fish ladder (Parana River, Brazil). The high ratio (72%) of fish in maturing gonadal development stages indicated that the fish were migrating for reproductive purposes. Fish ladder efficiency in Brazil was studied by Godinho *et al.* (1991) in the Tigucu River (upper Parana basin, southeastern Brazil). The ladder tested had 25 steps, was 78.3 m long and 10.8 m high. Of the 41 fish species captured in the region of the dam, 34 were present in the fish ladder but only 2% reached the upper section of the ladder. The most affected fishes were pimelodid catfishes.

3.4.2 Caribbean

Some of the more successful fisheries programs associated with dams are found in the Caribbean region. Sugunan (1997) conducted assessments of reservoir fisheries in Cuba. Fish is a major source of protein in Cuba but rivers contribute little in the way of fish yield to the country, primarily due to altered flow regimes resulting from dams, sedimentation, and altered river bed configurations. Reservoirs however contributed 19 000 t of the total 99 000 t/year of fish produced for the country, with tilapia and carp dominating the stocks. Average yield of 28 reservoirs was 125 kg/ha/year. Juarez-Palacios and Olmos-Tomassini (1992) calculated yields of cichlids in the 15 largest Cuban reservoirs for the period 1984-1988. They reported yields ranging from 11.5 kg/ha/year to 297.2 kg/ha/year (average 134.7 kg/ha/year).



Photo 11: Artisanal fishers exploit tilapia in a reservoir in the Dominican Republic. (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

Jackson (1985b) conducted fishery assessments of rivers and reservoirs in the Dominican Republic. Fishery yield estimates for reservoirs ranged from 29 kg/ha/year to 75 kg/ha/year. Prior to the construction of dams, river fisheries focused on crabs and marine fishes that ascended the country's

rivers. Small markets utilized the crab catch but there was little fisheries or market development for riverine finfish. Construction of hydroelectric dams throughout the country created reservoirs and tailwaters that were stocked with largemouth bass (*Micropterus salmoides*) and tilapia. These fishes expanded rapidly and were quickly recognized by local people as resource bases that could support recreational, artisanal and subsistence fisheries. Local markets accepted these new fish products and a tourist industry evolved around angling for largemouth bass. In tailwaters where flow was maintained, local fishermen harvested both species for subsistence purposes. In the reservoirs, most of the commercial and subsistence catch was tilapia. Primary challenges were access to ice, transportation of the catch, and safety concerns from fishermen encountering standing dead timber while fishing in small craft. Features limiting reservoir fisheries in the Dominican Republic were steep slopes, fluctuating water levels, and limited littoral zones for fish spawning. Additionally, dewatering of tailwaters in some of the systems precluded their contributions as fishery resources for surrounding communities.

3.4.3 Central America

In Central America, rivers tend to be short and have high gradients except for reaches near the narrow coastal zones. As a result, river fisheries have been small historically, albeit, utilized for traditional fisheries by indigenous peoples. Reservoirs have had an important role in expanding the base for inland fisheries in the region.



Photo 12: This highland reservoir in Panama accommodates a good carp, tilapia and peacock bass fishery. (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)



Photo 13: The Fortuna Reservoir in Panama, situated quite far upstream, is deep and has cold water; it only supports a limited fishery. The water is probably too cold to grow tilapia which are stocked in other Panamanian reservoirs. (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

A good example in this regard is the Republic of Panama. As has been the case for Caribbean nations, inland fisheries development in the Republic of Panama has been founded on introductions of exotic species. Peacock bass (*Cichla ocellaris*) was introduced into the Chagres River, and quickly moved from this river and throughout Gatun Lake, the principal reservoir for the Panama Canal (Zaret and Paine, 1973). The peacock bass is a top predator, and highly piscivorous (Zaret, 1979). It quickly decimated the native fish fauna but founded stocks that were conducive to fishery exploitation. Fishing cooperatives evolved. Yield was estimated at 4.8-5.3 kg/ha/year (Bayley, 1986; Maturell and Bravo, 1994). These cooperatives invested in fishing gear, ground transportation and marketing. Additionally, fishers not affiliated with the cooperatives established roadside stands where fish were sold. Recreational fisheries also evolved as the sporting qualities of peacock bass were discovered both by local Panamanians and by US military personnel stationed in nearby bases. Guide services soon followed and a small tourist industry for anglers was established (D.C. Jackson, Mississippi State University, USA, pers. observ., 1995; 1999).

Beyond Gatun Lake, peacock bass, common carp and tilapia were stocked in the interior regions of the country. These combinations successfully established fishery resources for local communities beyond the Canal Zone. Although nearly all of the reservoirs are situated in interior highlands, those at lower elevations have generally been more productive than those at higher elevations, primarily due to temperature influences (higher altitude reservoirs such as Fortuna Reservoir, maintained water too cool for the tropical cichlids) (D.C. Jackson, Mississippi State University, USA, pers. observ., 1984).

A special case in Panama is Bayano Lake. This lake was impounded in the 1970s and is the shallowest major reservoir in Panama (Maturell, 1984). The fishery of Bayano Lake has been fairly productive (63.2 kg/ha/year, Candanedo and D'Croze, 1983), and is apparently exploited primarily by indigenous peoples for subsistence purposes (D.C. Jackson, Mississippi State University, USA, pers. observ., 1984).

Prior to construction of the dam, numerous marine species ascended the river, and some of these fish became landlocked when the dam was closed. Over time, populations of these euryhaline fishes have declined in the reservoir. Tilapia are now in the system (R. Gonzales, University of Panama, pers.comm., 1999). Water quality has prevailing influences on fishery production potentials of this low-elevation reservoir (Candanedo and D’Croze, 1983), primarily as a result of decomposition of organic material.

3.5 North America, Europe and the Commonwealth of Independent States

In North America, dams have been responsible for development of highly productive reservoir (Hall and Van Den Avyle, 1986; Miranda and DeVries, 1996) and tailwater (Walburg *et al.*, 1981) fisheries, but have been problematic for migratory species such as anadromous salmonids. In the Columbia River, Eble *et al.* (1989) reported that fishing and alteration and degradation of river habitat from hydroelectric power dams, irrigation and exploitation of regional resources other than water have



Photo 14: The Bull Shoals Dam, which releases cold water, has changed the White River fishery from a natural world-class smallmouth bass and catfish fishery into a highly productive but artificial “put-and-take” tailwater fishery for rainbow trout. (Photo: D.B. Flynn, fishing consultant, Hot Springs, Arkansas, USA)

greatly altered the system, and have reduced annual returns of anadromous fish from about 10-16 million adults originally to about 2.5 million. Adult fishes must negotiate a variety of passages as well as the still waters of reservoirs in their attempt to reach upstream spawning areas. Young fish must travel downstream and negotiate the reservoirs and pass through or over the dams. High mortalities occur. Valuable fisheries have been severely impacted.

Of particular concern are salmon and steelhead stocks (*Oncorhynchus* spp.) in the Snake River, a principal tributary of the Columbia River. Four federal dams were constructed between 1962 and 1975. Wild salmon stocks that averaged more than 100 000 adults in the 1950s fell to 1 500 in 1995 (American Rivers and Trout Unlimited, 1999). All four Snake River salmon are listed as threatened or endangered and the Snake River steelhead (*Oncorhynchus mykiss*) is listed as threatened. Comprehensive investigations into the plight of spring and summer Chinook salmon (*O. tshawytscha*) in the system concluded that restoring some level of pre-dam ecosystem function has a high probability of achieving recovery for these fish (Nemeth and Kiefer, 1999). It is not only a question of restoring spawners to the system but in addition, providing nutrient transport from ocean environments into riverine environments via decomposing carcasses of adult fish post-spawning (Piorowski, 1995; Cederholm *et al.*, 1999).

In these and other systems of the northwestern USA, exotic species (e.g. smallmouth bass *Micropterus dolomieu* and channel catfish) have been introduced (Fletcher, 1991; Bennett *et al.*, 1991). Although these exotics are as yet not well accepted by the angling public, and generally are not considered commercial species, their popularity likely will increase as (or if) salmonid stocks in these impacted rivers continue to decline.

In the interior USA, dams have been constructed primarily for hydroelectric, navigation and flood control purposes. One of the first integrated systems in this regard was the Tennessee River, developed by the Tennessee Valley Authority (Voigtlander and Poppe, 1989). Impoundments were developed on the main channel as well as on tributary streams. Prior to impoundment, many of these streams had recreational fisheries for various centrarchid fishes, and in the higher elevation headwater reaches there were brook trout (*Salvelinus fontinalis*). The dams created slack water environments conducive for largemouth bass, crappies (*Pomoxis* spp.) and other sunfishes (*Lepomis* spp.), as well as for landlocked striped bass (*Morone saxatilis*). Large socio-economic enterprises developed around these fisheries. In tailwaters below dams, highly productive salmonid, sauger (*Stizostedion canadense*) and smallmouth bass fisheries evolved.

In the White River (Arkansas and Missouri, USA), a similar system was developed. Where once world class stream fishing for smallmouth bass existed, reservoir fisheries focused primarily on largemouth bass now prevail. Highly oxygenated hypolimnetic discharge from the hydroelectric dams proved too cool for native fishes and invertebrate fauna (Hoffman and Kilambi, 1971). To compensate for losses of these warmwater stream fisheries, trout (primarily rainbow trout *Oncorhynchus mykiss* and brown trout *Salmo trutta*) were introduced (Fry and Hanson, 1968). Hydropeaking discharges precluded substantial natural spawning of trout in these tailwater, so the fisheries are maintained by stocking from federal and state hatcheries (Baker, 1959). The trout grow exceptionally fast and attain very large size in the tailwaters (commonly > 10 kg). The tailwater trout fisheries have contributed substantially to supporting a multimillion dollar tourist industry (Baker, 1959) that makes significant economic contributions throughout the entire region (which continues, however, to be one of the poorer regions in the country). For example, along the White River below Bull Shoals Dam there are numerous privately-owned fishing resorts catering to sportfishing anglers. These resorts are assisted by local fishing guides and supported logistically by local businesses supplying goods and services (D.C. Jackson, Mississippi State University, pers. observ., 1965-1999). Similar tailwater fisheries for trout have been developed in Tennessee (Parsons, 1955).

In addition to tailwater fisheries, trout are stocked in the reservoirs, and live in the cold hypolimnion zones. These "multi-story" fisheries provide alternative trout fishing alongside warmwater fisheries in the reservoirs.



Photo 15: Jordan Dam on Coosa River supports a good tailwater fishery. (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

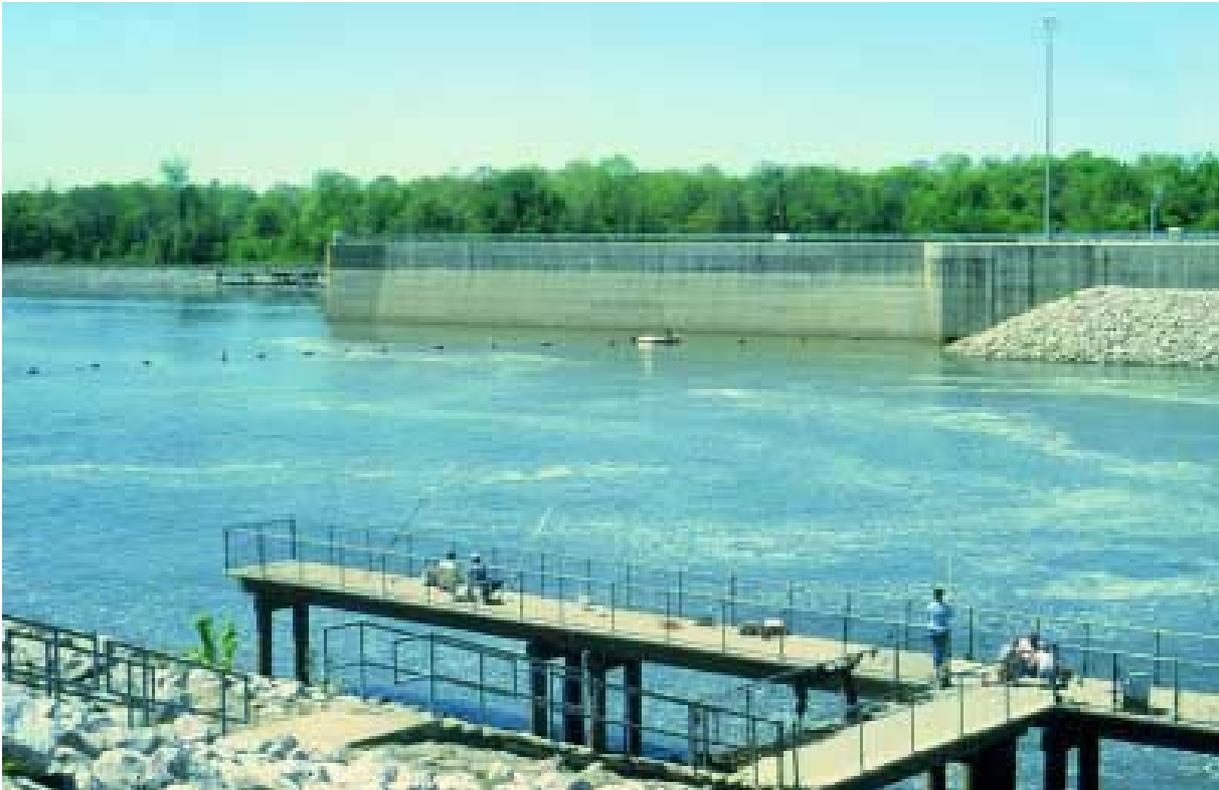


Photo 16: A fishing pier has been constructed by the U.S. Army Corps of Engineers to help anglers exploiting the tailwater fisheries of the Columbus Dam on Tombigbee Waterway (Tennessee, USA). (Photo: D.C. Jackson, Dept. of Wildlife and Fisheries, Mississippi State University, USA)

In the southeastern USA, the Tombigbee River historically was considered as one of the more biologically rich and diverse riverine ecosystems in the entire country (Boschung, 1987). The river was comprehensively modified by construction of the Tennessee-Tombigbee Waterway to become a series of slack-water pools and artificial canals, linked by dams and locking systems (Jackson, 1995). Prior to construction of the waterway, the river supported limited local fisheries, primarily for catfishes and centrarchids. With the advent of the waterway, several large reservoirs and numerous tailwaters were established. The reservoirs are relatively shallow with high degrees of shoreline development conducive to production of centrarchid fishes (primarily largemouth bass, crappies, sunfishes). The tailwaters are highly productive for catfishes, crappies and centrarchid basses (Jackson and Dillard, 1993). Fisheries for white bass (*Morone chrysops*) are developing. The cutoff bendways (old river channels) are excellent crappie fisheries (Sarnita, 1991). Ultimately, these bendways may develop into oxbow lakes as they become isolated from the main channel by sedimentation processes (Jackson, 1995).

Moffett (1949) reported that flows from Shasta Dam on the Sacramento River (California, USA) benefitted salmon and trout in the river below the dam by stabilizing physical environmental features. Flow reductions resulting from operation of dams, however, can negatively impact fish stocks (Bain and Boltz, 1989). Whitley and Campbell (1974) studied the effects of flow reduction resulting from dams on the Missouri River (USA) and demonstrated significant reductions in the amount of inundated floodplain. Reduction of inundated floodplains can result in reduced fish stocks in river-floodplain ecosystems (Welcomme, 1985; Junk *et al.*, 1989; Jackson and Ye, 2000). In a 145 km long reach of the Missouri River, flow regulation resulted in a 67% loss of inundated floodplain area and a greater than 80% decrease in fish catch (Whitley and Campbell, 1974). Declining harvest downstream from dams on the Missouri River also may be the result of physical degradation of channels coupled with fluctuating water levels (Hess *et al.*, 1982). Reservoirs on the Missouri River act as sediment traps. Discharge of clear water accelerates erosion downstream from dams and ultimately can lead to dewatering of backwater areas. This can result in reduced fish production from backwaters as well as stranding of fish.

The Pascagoula River (Mississippi) is the largest physically unmodified river ecosystem in the lower 48 states of the continental USA (Dynesius and Nilsson, 1994). It is located in the state of Mississippi and drains directly into the Gulf of Mexico. One of its principal tributaries, the Bouie River, flows near the city of Hattiesburg, Mississippi. There is, currently, a proposal to construct one or two dams on the Bouie River, primarily to enhance the water supply for the city and surrounding region. First-order estimates of fish yields from the proposed reservoirs (using models advanced earlier in this report) indicated that reservoir fisheries from the reservoirs would compensate for losses sustained from the river. However, there are two fishes found in the Bouie River that are listed as threatened species: the gulf sturgeon *Acipenser ohrhynchus desotoi* (Zehfuss *et al.*, 1999), and the pearl darter *Percina aurora* (Ross, in press). On 14 October 1999, a meeting was convened by D. Jackson (co-author of this chapter) at Mississippi State University (USA) to share information and discuss the issues regarding impoundment of this river. Participants at the meeting were representatives from state and federal natural resources agencies, academic institutions, engineering and environmental consulting firms, conservation organizations, and a local citizens group. It was generally determined that fisheries *per se* were not the critical issues, but that the welfare of the sturgeon and the darter, as well as the physical and biological integrity of the river ecosystem, were of national and international significance. Support from participants representing biological, ecological and natural resources professions was stated as critical to advancing the impoundment project on the Bouie River. This support was not forthcoming.

Lelek (1989) reported maximum fish yields in the High Rhine stretch of the River Rhine (Germany) at 37.6 kg/ha/year and for the lower Rhine at 45 kg/ha/year. Impounded reservoirs in the High Rhine stretch yielded 21.1 to 61.8 kg/ha/year but the highest value (67.7 kg/ha/year) was associated with a flowing stretch of the river between two dams. In the Upper Rhine stretch, reservoir yield was

reported at 42.4 kg/ha/year, while the regularly flooded backwaters historically provided a yield of 115 kg/ha/year.

Backiel and Penczak (1989) reported yields from the Vistula River (Poland) at 26 kg/ha/year. Bacalbasa-Dobrovici (1989) reported yields for the Danube River in Germany at 65-76 kg/ha/year and in Austria at 32 kg/ha/year. Total fish yield from the lower Danube River is approximately half the yield obtained from the river prior to changes by hydraulic works.

Karpova *et al.* (1996) documented fisheries characteristics for 49 reservoirs on rivers in the Commonwealth of Independent States (CIS; former USSR). Fish yields over a 12-year period (1980-1991) ranged from 0.14 kg/ha/year in the coolest, most northerly reservoirs, to 48.11 kg/ha/year in a Ukrainian reservoir. They noted also that CIS reservoirs in Central Asia and Kazakhstan have fairly low yields (average 11.48 kg/ha/year) but that this may be more related to cultural and local factors (e.g. preference for red meat rather than fish; distance to markets) than to productive potentials of the reservoirs.

4. CONCLUSIONS

Dams alter river ecosystems and subsequently require development of new relationships between humankind and natural resources associated with these ecosystems. We build dams because we perceive that benefits will accrue to us from them in the form of energy, water supply, transportation, flood control, fishing, recreation, aesthetics, and so on. We must, however, be on guard against developing arrogance with respect to ecosystems and the resources they afford (Catton and Dunlap, 1980), and also with respect to the persons who interact consumptively or otherwise with these resources and who may have little if any voice in decision-making processes. From the human dimension perspective, this is particularly the situation when the resources are non-portable natural resources (e.g. a river and its fish stocks). Persons linked to river fisheries through culture, tradition and economics incorporate these fisheries as dominant components of their human identities (Brown *et al.*, 1996; Jackson, 1991). Reorientation of their values and activities after impacts to or loss of the foundation for their identities can generate considerable socio-economic stress to these people, their communities and their cultures (Baird, 1994; Brown *et al.*, 1996).

From a fishery perspective, dams and their resulting reservoirs can benefit human societies. Dams, however, usually alter traditional riverine fisheries, sometimes positively (i.e. from tailwater fisheries), but more commonly negatively. There typically are faunal shifts from river-adapted species to those more adapted to lentic environments. Species diversity in impoundments usually declines over time as river-adapted species fade from the system. Benefits from impoundment of rivers seem to be more pronounced for smaller, shallower reservoirs that have reasonably high concentrations of dissolved solids and that are located in the upper reaches of their respective river ecosystem. However, several such impoundments within the same river catchment can result in synergistic negative impacts to the downstream fisheries. Introduction of exotic species (both in reservoirs and in tailwaters) can enhance yields, as long as the exotic fishes are environmentally sound and culturally acceptable to the surrounding human population. Although management of dams can result in acceptable fisheries, when such management is, however, focused solely on fisheries, specific needs of fish species not included in the fishery, and/or that may be threatened or endangered, are at risk of being overlooked.

Compensation for loss in yield from river fisheries can be difficult to achieve through development of reservoir fisheries. Loss in fish yield is assumed also to be loss with respect to human nutrition, primarily protein. The larger the river, and the more downstream the location of the dam, the less potential there is for a reservoir fishery to compensate (in terms of yield) for losses sustained by the river fishery. In this regard, mitigation emphasis should concentrate on surface to volume ratios, and temperature regimes for the reservoirs. Compensation potentials apparently are higher in shallower reservoirs and in tropical regions than they are in deeper reservoirs and in more northern latitudes. If

fisheries are directed to stocks of migratory fishes, dams can be disastrous, both to riverine fisheries and, in some cases, to ocean fisheries (e.g. anadromous salmonids). There are, however, exceptions where a dam apparently didn't harm the river fishery. Petr (pers.comm., 2000) emphasizes that, for example, Lake Volta dam at Akosombo (Ghana), is located not very far from the sea and that Lake Volta which extends over several hundred kilometers also floods extensive shallows, thus positively influencing fishery production in this system.

If seasonal flood pulses are lost as a result of dams, there can be substantial losses to the fisheries of floodplain river ecosystems (*sensu* Welcomme, 1985; Junk *et al.*, 1989). Additionally, and because dams tend to be constructed to enhance socio-economic development activities, they tend to attract people and industry. Subsequently, river ecosystems containing dams must contend with pollution and increased exploitation and extraction of their resources, pressures independent from, but adding to, the direct influences of dams and reservoirs on the physical and biological dimensions of the system. Given the above concerns, regions lacking naturally substantial riverine fishery resources and/or river fisheries tend to derive the greatest degree of net benefit from development of reservoir fisheries (e.g. Dominican Republic, Sri Lanka, Republic of Panama). Caution, however, is warranted when fisheries development is conducted in the context of cultures where fishing and fish consumption is not a tradition. Otherwise, the potentials for altering riverine fisheries as a result of damming rivers must be acknowledged.

We can, however, look at the issue of dams on rivers from an entirely different perspective. If our spatial scale is large enough (planetary, continental, perhaps regional and biome), and our temporal scale is long enough (decades, centuries, millennia), placing a dam on a river does little more than increase atmospheric water vapour (through evaporation from the impoundment, which can be extreme in more arid environments; Petr and Mitrofanov, 1998), reduce long-term streamflows downstream (Jackson and Davies, 1988a and 1988b; Jackson *et al.*, 1991), desiccate terrestrial environments, salinate surrounding areas, and shift bio-energetic processes (some of which can lead to floral and faunal extinction at various scales of resolution). We cannot assign the terms "good" or "bad" to any of these phenomena. They simply reflect anthropogenic activity on the planet. However, if we look at smaller spatial and shorter temporal scales, which we obviously cannot neglect as we have to make decisions that have bearings on the present and future human generations but also on present and future living aquatic resources, we have to keep in mind that dams and their reservoirs, which can under certain circumstances help to better nourish people and make their livelihoods more sustainable, can - if wrongly placed - also lead to significant declines of fisheries and to extinction of aquatic species.

Given sufficient time, geophysical and climatic forces will override and erode the physical influences of dams, and evolutionary forces will alter how life forms interact with the resulting environments. Whether or not humans as a species will be included in these processes is not known. Our perspective is too short. But short-term (typically ca. 100 years) perspective is fundamental to construction of dams. Eternity, as a concept, is too big for us. We do not usually project caring, or our sense of responsibility, beyond three or perhaps four human generations. Beyond that, people (if there are any) must be able to take care of themselves. Nature does not care. It is we who (hopefully) care and who must assume responsibility.

The integrity of rivers is challenged by human demands for their products and buffering from their processes. As co-evolutionary components of this planet, humans utilize and modify rivers and their associated resources to meet real or perceived needs. We have used rivers as highways for exploration and conquest and to address basic human needs. We use rivers to transport goods, services and wastes. We have harnessed the waters and the energy of rivers to protect and power ourselves and our civilizations. Our use of rivers has led to our encroachment on them. These anthropogenic activities alter how rivers function and thus how we function with them.

Prevailing intentions are almost always good; designed to advance human civilization and/or alleviate human suffering. At some point, however, we must ask ourselves if we really know enough to make

decisions about the future of rivers, decisions that if wrong, can degrade human civilization and increase human suffering. These questions rightly temper our hearts as we ponder the legacy we leave for future generations.

Though trained and disciplined in technology, engineering and the sciences, we who practice these professions realize that ultimately decisions cannot be made solely through mental processes. There are indeed dimensions of the human experience that transcend reason and logic. We discover that if we rely on our minds in decision-making processes, we will be correct most of the time. However, if we add the dimension of the human heart to our decisions, we can substantially increase the probability of being right. This does not discount professional objectivity but rather expands the data bases from which we operate. It underscores the reality that we are humans and should act like humans; and that we must remember that there are other humans who are depending on us, the scientists, the resource managers, the decision-makers, to be right.

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ENVIRONMENTAL ISSUES, DAMS AND FISH MIGRATION

by

Michel Larinier
CSP CEMAGREF GHAPE
Institut de Mécanique des Fluides
Avenue du Professeur Camille Soula
31400 Toulouse, France

EXECUTIVE SUMMARY

Fish populations are highly dependent upon the characteristics of their aquatic habitat which supports all their biological functions. Migratory fish require different environments for the main phases of their life cycle which are reproduction, production of juveniles, growth and sexual maturation. The life cycle of diadromous species takes place partly in fresh water and partly in sea water: the reproduction of anadromous species takes place in freshwater, whereas catadromous species migrate to the sea for breeding purposes and back to freshwater for trophic purposes. The migration of potamodromous species, whose entire life cycle is completed within the inland waters of a river system, must also be considered.

The construction of a dam on a river can block or delay upstream fish migration and thus contribute to the decline and even the extinction of species that depend on longitudinal movements along the stream continuum during certain phases of their life cycle. Mortality resulting from fish passage through hydraulic turbines or over spillways during their downstream migration can be significant. Experience gained shows that problems associated with downstream migration can also be a major factor affecting anadromous or catadromous fish stocks. Habitat loss or alteration, discharge modifications, changes in water quality and temperature, increased predation pressure as well as delays in migration caused by dams are significant issues.

The upstream passage for anadromous and potamodromous species past obstacles can be provided for through several types of fishways: pool-type fish passes, Denil fish passes, nature-like bypass channels, fish lifts or locks, collection and transportation facilities. Only few special designs have been developed in Europe, Japan, New Zealand and Australia for catadromous species, namely for eels.

The critical point in upstream fish passage design is the location of the fish pass entrance and the attraction flow, which must take into account river discharge during the migration period and the behaviour of the target species in relation to the flow pattern at the base of the dam. Some sites may require several entrances and fish passes.

The downstream migration problems have not been as well studied or fully considered as those associated with upstream migration. The accepted downstream passage technologies to exclude fish from turbines are physical screens, angled bar racks and louvers associated with surface bypasses. Behavioural guidance devices (attraction or repulsion by lights, sound, electricity) have not been proven to perform successfully under a wide range of conditions and are still considered as experimental.

A non-exhaustive review of the current status of the use of fish facilities at dams throughout the world is presented, with the main target species considered from North America, Western Europe, Eastern Europe, Latin America, Africa, Australia, New Zealand, Japan and Asia.

The most frequent causes of fish pass failure include lack of attraction flow, unsuitable location of the entrance, inadequate maintenance, hydraulic conditions (flow patterns, velocities, turbulence and aeration levels) in the fish pass not adapted to the target species.

Upstream passage technologies can be considered well-developed only for a few anadromous species including salmonids (e.g. Atlantic and Pacific salmon, sea-run trout) and clupeids (e.g. American and Allis shad, alewives, blueback herring) in North America and Europe.

There is an urgent need for better biological information (e.g. migration period, swimming capacity, migratory behaviour) and to do fish passage research (upstream and downstream) for other native species.

Effectiveness of a fish pass is a qualitative concept which consists in checking that the pass is capable of letting all target species through within the range of environmental conditions observed during the migration period. Effectiveness may be measured through inspections and checks: visual inspection, trapping, video checks.

The efficiency of a fish pass is a more quantitative description of its performance. It may be defined as the proportion of stock present at the dam which then enters and successfully moves through the fish pass in what is considered an acceptable length of time. The methods giving an insight into the efficiency of a pass are more complicated than those for effectiveness. Marking and telemetry are valuable techniques to assess the overall efficiency of fish passes and the cumulative effect of various dams along a migration path.

The targeted effectiveness for a given site must be defined with respect to the biological objectives sought. It is therefore related to the species considered, the number of obstacles on the river and the position of the obstacle on the migration route.

The fact that almost nothing is known about migrating species, particularly in developing countries, must not be a pretext to do nothing at a dam. In the absence of good knowledge on the species, the fish passes must be designed to be as versatile as possible and open to modifications. Some fish passes are more suitable than others when targeting a variety of migratory species, such as vertical slot passes with successive pools. Devices to monitor fish passage must be installed. This monitoring process will enable the fish pass to be assessed and the feedback thus obtained may be useful for other fish pass projects in the same regional context.

For high dams, when there are numerous species of poorly-known variable swimming abilities, migratory behaviour and population size, it is best to initially concentrate mitigation efforts on the lower part of the fish pass, i.e. to construct and optimize the fish collection system including the entrance, the complementary attraction flow and a holding pool which can be used to capture fish to subsequently transport them upstream, at least in an initial stage.

Fish pass design involves a multidisciplinary approach. Engineers, biologists and managers must work closely together. Fish passage facilities must be systematically evaluated. It should be remembered that the fish pass technique is empirical in the original meaning of the term, i.e. based on feedback from experience. The most significant progress in fish passage technology has been made in countries which systematically assessed the effectiveness of the passes and in which there was a duty to provide monitoring results.

One must never lose sight of the limits to the effectiveness of fish passes. In addition to problems relating to fish passage at obstacles, there are indirect effects of dams which may prove of major significance such as changes in flow, water quality, the increase in predation and drastic changes to the habitat upstream or downstream. The protection of migratory species for a given dam must be studied in a much wider context than the strict respect of fish passage alone.

1. FISH MIGRATION

Fish populations are highly dependent upon the characteristics of the aquatic habitat which supports all their biological functions. This dependence is most marked in migratory fish which require different environments for the main phases of their life cycle which are reproduction, production of juveniles, growth and sexual maturation. The species has to move from one environment to another in order to survive.

It has become customary to classify fishes according to their capacity to cope during certain stages of their life cycle with waters of differing salinities (McDowall, 1988).

The entire life cycle of the **potamodromous** species occurs within fresh waters of a river system (Northcote, 1998). The reproduction and feeding zones may be separated by distances that may vary from a few metres to hundreds of kilometres.

The life cycle of the **diadromous** species takes place partly in fresh and partly in marine waters, with distances of up to several thousands of kilometres between the reproduction zones and the feeding zones.

Two different groups can be distinguished in the category of diadromous species:

- **Anadromous** species (e.g. salmon), whose reproduction takes place in freshwater with the growing phase in the sea. Migration back to freshwater is for the purpose of breeding.
- **Catadromous** species (e.g. eel) have the reverse life cycle. Migration to the sea serves the purpose of breeding and migration back to freshwater is a colonisation for trophic purpose. Catadromy is much less common than anadromy.

Anadromous species recognize their native river catchment and return there, with a low rate of error, to reproduce. This phenomenon of returning to their river of birth (“homing”) depends principally on olfactory recognition of streams. Consequently, each river basin has a stock of its own which is a unique unit.

Amphidromous (e.g. striped mullet) species spend parts of their life cycle in both fresh and marine waters. Their migration is not for the purpose of breeding but is typically associated with the search for food and/or refuge.

There are about 8 000 species of fish which live in freshwater and a further 12 000 which live in the sea; and there are about 120 species which move regularly between the two (Cohen, 1970).

2. EFFECT OF DAMS ON FISH COMMUNITIES

The building of a dam generally has a major impact on fish populations: migrations and other fish movements can be stopped or delayed, the quality, quantity and accessibility of their habitat, which plays an important role in population sustainability, can be affected. Fish can suffer major damage during their transit through hydraulic turbines or over spillways. Changes in discharge regime or water quality can also have indirect effects upon fish species. Increased upstream and downstream predation on migratory fish is also linked to dams, fish being delayed and concentrated due to the presence of the dam and the habitat becoming more favourable to certain predatory species.



Photo 1: Aerial view of Bonneville Dam on the Columbia River (USA). (Photo Larinier)



Photo 2: The Gouet dam is blocking the migration of salmon on the Gouet river (Britanny, France). (Photo Larinier)

2.1 Upstream Migration

One of the major effects of the construction of a dam on fish populations is the decline of anadromous species. The dam prevents migration between feeding and breeding zones. The effect can become severe, leading to the extinction of species, where no spawning grounds are present in the river or its tributary downstream of the dam.



Photo 3: The 44 m high Kali Gandaki “A” Hydroelectric Dam (Nepal), which was still under construction in 2001, cuts off local fish species, e.g. *Tor* sp. and *Bagarius bagarius*, from their valuable spawning grounds upstream. (Photo Marmulla)

Since the nineteenth century, there has been a continuous and increasing decline in stocks of diadromous species in France: in a large majority of cases, the main causes of decline have been the construction of dams preventing free upstream migration. The negative effects of these obstructions on anadromous species (particularly Atlantic salmon and Allis shad) have been much more significant than water pollution, overfishing and habitat destruction in the main rivers. Obstructions have been the reason for the extinction of entire stocks (salmon in the Rhine, Seine and Garonne rivers) or for the confinement of certain species to a very restricted part of the river basin (salmon in the Loire, shad in the Garonne or Rhône, etc.) (Porcher and Travade, 1992). Sturgeon stocks have been particularly threatened by hydroelectric dams on the Volga, Don and Caucasian rivers (Petts, 1988). On the East Coast of the USA, the building of dams has been identified as the main reason for the extinction or the depletion of migrating species such as salmon and shad on the Connecticut, Merrimack and Penobscott rivers (Baum, 1994; Meyers, 1994; Stolte, 1994).

Zhong and Power (1996) reported that the number of fish species decreased from 107 to 83 because the migration was interrupted by the Xinanjiang dam (China). The reduction of biodiversity occurred not only in the flooded section but also in the river below the dam. Quiros (1989) mentions that dam construction in the upper reaches of Latin American rivers appears to lead to the disappearance of potamodromous species stocks in reservoirs and in the river upstream of the structure. The same occurs in reaches where a whole series of dams and reservoirs have been constructed.



Photo 4: Navigation dams on the Seine river have been the main reason for the extinction of entire stocks of diadromous species in the river Seine (France). (Photo Larinier)



Photo 5: The Karapiro dam on the Waikato river (New Zealand) is one of the numerous obstacles that prevented migratory fish (particularly eels) to pass upstream. (Photo Larinier)

In Australia, obstructed fish passage has led to many instances of declining populations or extinctions of species in the affected basin (Barry, 1990; Mallen-Cooper and Harris, 1990).

The concept of obstruction to migration is often associated with the height of the dam. However, even low weirs can constitute a major obstruction to upstream migration. Whether an obstacle can be passed or not depends on the hydraulic conditions over and at the foot of the obstacle (velocity, depth of the water, aeration, turbulence, etc.) in relation to the swimming and leaping capacities of the species concerned. The swimming and leaping capacities depend on the species, the size of the individuals, their physiological condition and water quality factors as water temperature and dissolved oxygen. Certain catadromous species have a special ability to clear obstacles during their upstream migration: in addition to speed of swimming, the young eels are able to climb through brush, or over grassy slopes, provided they are kept thoroughly wet; some species (i.e. gobies) possess a sucker and enlarged fins with which they can cling to the substrate and climb around the edge of waterfalls and rapids (Mitchell, 1995).

For any given target species, an obstruction may be total, i.e. permanently insurmountable for all individuals. It may be partial, i.e. passable for certain individuals. It may be temporary, i.e. passable at certain times of the year (under certain hydrological or temperature conditions). During low flow conditions weirs may be insurmountable because the depth of water on the face is too shallow to permit fish to swim. They may however become passable at a higher discharge rate, as water depth increases and the fall at the structure generally decreases. The negative impact on fish caused by temporary obstacles, which delay them during migration and which may cause them to stay in unsuitable zones in the lower part of the river, or cause injury as a result of repeated, fruitless attempts to pass, must not be underestimated.

2.2 Downstream Migration

In the first stages of dam development, engineers and fisheries biologists were preoccupied with providing upstream fish passage facilities. Passage through hydraulic turbines and over spillways was not considered to be a particularly important cause of damage to downstream migrating fish. Experience has shown that problems associated with downstream migration can be major factors affecting diadromous fish stocks.

Downstream migration involves diadromous species: juveniles of anadromous species, adults of catadromous species and certain anadromous species (repeat spawners). For potamodromous species, downstream fish passage at hydroelectric power dams is generally considered less essential in Europe and North America. However, certain potamodromous species can migrate over very long distances, so the need for mitigation to provide passage for potamodromous fish must be considered species- and site-specific.

2.2.1 Damage Due to Hydraulic Turbines

Fish passing through hydraulic turbines are subject to various forms of stress likely to cause high mortality: probability of shocks from moving or stationary parts of the turbine (guide vanes, vanes or blades on the wheel), sudden acceleration or deceleration, very sudden variations in pressure and cavitation. Numerous experiments have been conducted in various countries (USA, Canada, Sweden, Netherlands, Germany and France), mainly on juvenile salmonids and less frequently on clupeids and eels, to determine the mortality rate due to their passage through the main types of turbine (Bell, 1981; Monton, 1985; Eicher, 1987; Larinier and Dartiguelongue, 1989; EPRI, 1992).

The mortality rate for juvenile salmonids in Francis and Kaplan turbines varies greatly, depending on the properties of the wheel (diameter, speed of rotation, etc), their conditions of operation, the head, and the species and size of the fish concerned. The mortality rate varies from under 5% to over 90% in

Francis turbines. On average, it is lower in Kaplan turbines, from under 5% to approximately 20%. The difference between the two types of turbine is due to the fact that Francis turbines are generally installed under higher heads.

Mortality in adult eels (*Anguilla* spp.) is generally higher, because of their length. The mortality rate may be 4 to 5 times higher than in juvenile salmonids, reaching a minimum of 10% to 20% in large low-head turbines (as against a few per cent in juvenile salmonids), and more than 50% in the smaller turbines used in most small-scale hydroelectric power plants (Desrochers, 1994; Hadderingh and Bakker, 1998; Monten, 1985; Larinier and Dartiguelongue, 1989).

The mortality rate may be higher for certain species. In physostomous species (e.g. salmonids, clupeids and cyprinids), the pressure in the swim bladder can be regulated relatively quickly through the air canal and the mouth, and these species will resist sudden variations in pressure. In physoclistic species (e.g. percids), pressure is regulated much more slowly by gaseous exchange with the blood vessels in the wall of the swim bladder. The risk of rupturing the swim bladder following a sudden drop in pressure is thus much greater and physoclistic fish are thus much more susceptible to variations in pressure (Tsvetkov *et al.*, 1972; Larinier and Dartiguelongue, 1989).

2.2.2 Damage Due to Spillways

Passage through spillways may be a direct cause of injury or mortality, or an indirect cause (increased susceptibility of disorientated or shocked fish to predation). The mortality rate varies greatly from one



Photo 6: Spillway on the Garonne river (France).

location to another: between 0% and 4% for the Bonneville, McNary and John Day dams (about 30 m high spillways) on the Columbia River, 8% at the Glines dam (60 m high spillway) and 37% at the Lower Elwha dam (30 m high spillway) on the Elwha river for juvenile salmonids (Bell and Delacy, 1972; Ruggles and Murray, 1983).

Mortalities have several causes: shearing effects, abrasion against spillway surfaces, turbulence in the stilling basin at the base of the dam, sudden variations in velocity and pressure as the fish hits the water, physical impact against energy dissipators. The manner in which energy is dissipated in the spillway can have a determinant effect on fish mortality rates.

Experiments have shown that significant damage occurs (with injuries to gills, eyes and internal organs) when the impact velocity of the fish on the water surface in the downstream pool exceeds 16 m/s, whatever its size (Bell & Delacy, 1972). A column of water reaches the critical velocity for fish after a drop of 13 m. Beyond this limit injuries may become significant and mortality will increase rapidly in proportion to the drop (100% mortality for a drop of 50-60 m).

Passage through a spillway under free-fall conditions (i.e. free from the column of water) is always less hazardous for small fish, insofar as their terminal velocity is less than the critical velocity. For larger fish, the hazards are identical whether they pass under free-fall conditions or are contained in the column of water.

“Ski jump” spillways are preferable to other types of spillway, because the abrasion on the spillway face is eliminated, and, especially for small fish if the fish fall freely outside the column of water and on the condition that there is a pool of a sufficient volume at its base.

For dams of moderate heights (less than 10 metres), spillways are most often considered to be the safest way for downstream migrating fish to pass a dam, on condition there is sufficient depth at the base of the dam and no over-aggressive baffles (pre-cast blocks, riprap, etc.).

2.2.3 Delays in Migration

Impoundments can have an effect on the timing of fish downstream migration. In the Columbia basin, during low flows, juvenile Chinook salmon reach the estuary about 40 days later than they did before the dams were constructed: impoundments of river flows by dams have more than doubled the time required for migration of juveniles to the sea. Such delays can have a rather drastic effect by exposing fish to intensive predation, to nitrogen supersaturation and several other hazards such as exposure to disease organisms and parasites. The delay can also result in a significant portion of the juvenile population residualizing and spending several months in fresh water (Ebel, 1977).

2.3 Loss of Habitat

Dam construction can dramatically affect migratory fish habitat. The consequence of river impoundment is the transformation of lotic environment to lentic habitats. Independently of free passage problems, species which spawn in relatively fast flowing reaches can be eliminated. From a study of the threatened fish of Oklahoma, Hubbs and Pigg (1976) suggested that 55% of the man-induced species depletions had been caused by the loss of free-flowing river habitat resulting from flooding by reservoirs, and a further 19% of the depletion was caused by the construction of dams, acting as barriers to fish migration.

About 40% of the spawning grounds in the Qiantang river above the Fuchunjiang dam were lost by flooding (Zhong and Power, 1996). On the Indus river, the construction of the Gulam Mahommed

Dam has deprived the migratory *Hillsa ilisha* of 60% of their previous spawning areas (Welcomme, 1985). On the Columbia river and its main tributary the Snake river, most spawning habitat were flooded, due to the construction of dams creating an uninterrupted series of impoundments (Raymond, 1979).

The suppression of flood regime downstream from an impoundment by means of flow regulation, can deprive many fish species of spawning grounds and valuable food supply (Petts, 1988). This can lead to changes in species composition with loss of obligate floodplain spawners. Dam construction for industrial uses within the Rio Mogi Guassu Brazil has resulted in the progressive loss of flood plain wetlands (Godoy, 1975). The cumulative effect of diminished peak discharges, stabilized water levels, reduced current velocities and water temperature eliminated spawning grounds below the dams on the Qiantang and Han rivers : six migratory fish and five species favouring torrential habitats declined severely (Zhong and Power, 1996). The reaction of the fish communities of the Chari, Niger and Senegal rivers to flood failures provoked by natural climatic variations illustrates the highly detrimental effect of suppressing the flood (Welcomme, 1985).

2.4 Modification of Discharge

The modification of downstream river flow characteristics (regime) by an impoundment can have a variety of negative effects upon fish species: loss of stimuli for migration, loss of migration routes and spawning grounds, decreased survival of eggs and juveniles, diminished food production.

Regulation of stream flow during the migratory period can alter the seasonal and daily dynamics of migration. Regulation of a river can lead to a sharp decrease in a migratory population, or even to its complete elimination. Any reduction in river discharge during the period of migratory activity can diminish the attractive potential of the river, hence the numbers of spawners entering the river is



Photo 7: Drastic reduction of flow downstream a dam on the Rhône river (France). (Photo Croze)



Photo 8: Drastic reduction of flow downstream a dam in New-Zealand. (Photo Larinier)

reduced. Because of this, regulation of a river can greatly influence the degree of migration to the non-regulated part of the river below the dam site. During the initial flooding of the Tsimlyanskoye reservoir, two species *Acipenser güldenstädti* (Russian sturgeon) and *Huso huso*, which hitherto spawned in the Don above the confluence of the Severtskiy Donets, entered the tributary where they had not previously been known to breed (Pavlov, 1989).

Zhong and Power (1996) noted that high discharge is important for inducing anadromous species to ascend rivers to spawn : after the construction of the Fuchunjiang dam on the Qiantang river, there was a significant correlation between the capture of an anadromous fish *Coilia ectenes* ascending the river to spawn and the amount of the discharge from the project.

Variable flow regime resulting from operation of hydroelectric power-dams can have significant consequences for fish fauna : daily 2 m to 3 m fluctuation of Colorado river-levels below the Glen Canyon dam may have contributed to the decline in endemic fish (Petts, 1988). The native species have been replaced by the introduced species and spawning of the native species is restricted to tributaries. Walker *et al.* (1979) related the disappearance of *Tandanus tandanus* in the Murray river, Australia to short-term fluctuations in water level caused by reservoir releases in response to downstream water-user requirements.

The fluctuations of water-level and velocities due to power demand could have disastrous effects on fish: spawning behaviour could be inhibited, juveniles could be swept downstream by high flows, sudden reductions in flow could leave eggs or juveniles stranded (Petts, 1988).

2.5 Water Temperature and Water Quality Changes

Dams can modify thermal and chemical characteristics of river water : the quality of dam-releases is determined by the limnology of the impoundment, with surface-release reservoirs acting as nutrient traps and heat exporters and deep-release reservoirs exporting nutrient and cold-waters (Petts, 1988). This can affect fish species and populations downstream.

Water temperature changes have often been identified as a cause of reduction in native species, particularly as a result of spawning success (Petts, 1988). Cold-water release from high dams of the Colorado river has resulted in a decline in native fish abundance. (Holden and Stalnaker, 1975). The fact that *Salmo spp.* had replaced some twenty native species has been attributed to the change from warm-water to cold-water.

Water-chemistry changes can also be significant for fish. Release of anoxic water from the hypolimnion can cause fish mortality below dams (Bradka and Rehackova, 1964).

During high water periods, water which spills over the crest of the dam can become over-saturated with atmospheric gases (oxygen and nitrogen) to a level which can be lethal for fish. Mortality can result from prolonged exposure to such lethal concentrations downstream of the spillways. Substantial mortalities of both adult and juvenile salmonids caused by high spillway flows which produced high supersaturation (120-145%) have been observed below the John Day dam on the Columbia river (Raymond, 1979). The Yacyreta dam on the Parana river generates supersaturated levels of total dissolved gases that can affect the health condition of fish: in 1994, massive fish mortality was observed in a 100 km reach below the dam (Bechara *et al.*, 1996).

2.6 Increased Exposure to Predation

Normal predation behaviour may become modified with the installation of a dam, and although few data exist to date, it appears that migrating species suffer increased predation in the vicinity of an installation, whether by other fish or birds. This may be due to the unnatural concentration of fish above the dam in the forebay, or to fish becoming trapped in turbulence or recirculating eddies below spillways, or to shocked, stressed and disoriented fish being more vulnerable to predators after turbine passage. In some rivers or hydroelectric schemes, predation may affect a substantial proportion of the fish population. On the Columbia river, predator exposure associated to turbine passage was the major causes of salmon mortality. Tests at the Kaplan turbines indicated a mean loss of 7% and studies showed that the indirect mortality on juvenile coho salmon could reach 30% when indirect mortality from predation was included (Ebel *et al.*, 1979).

3. RESTORATION OF UPSTREAM LONGITUDINAL CONNECTIVITY

3.1 Upstream Fish Passage Facilities

The general principle of upstream fish passage facilities (or fish passes) is to attract migrants to a specified point in the river downstream of the obstruction and to induce them (actively), or even make them (passively), pass upstream, by opening a waterway (*fish pass* in the strict sense) or by trapping them in a tank and transferring them upstream (fish lift or transport systems such as trucking).

Upstream passage technologies are considered to be well-developed for certain anadromous species including mainly salmonids (e.g. salmon, trout) and clupeids (e.g. shad, alewives, blueback herring) in North America and Europe. Upstream passage can be provided through several types of fish pass:

pool-type fish passes, Denil type fish pass (or baffle-type fish passes), nature-like bypass channels, fish lifts and fish locks, collection and transportation facilities. Special designs for catadromous species have been developed in Europe, Japan, New Zealand and Australia, namely for eel.

The design of a fish pass should take into account certain aspects of the behaviour of migratory species. In particular, its effectiveness is closely linked to water velocities and to flow patterns in the facility. The water velocities in the fish pass must be compatible with the swimming capacity and behaviour of the species concerned. Some species are very sensitive to certain flow regimes or conditions: water level differences between pools which are too large, excessive aeration or turbulence, existence of large eddies and flow velocities which are too low can act as a barrier for fish. In addition to hydraulic factors, fish are sensitive to other environmental parameters (level of dissolved oxygen, temperature, noise, light, odour, etc.) which can have a deterrent effect. This applies particularly if the quality of the water feeding the fish pass is different to that passing across the dam (low oxygen levels, differences in temperature and odour, etc.).

3.2 Pool-type Fish Passes

Pool-type fish passes, which are widely-used, are a very old concept. An official survey carried out in France in the last century (Philippe, 1897) revealed that there were more than one hundred. The principle behind pool passes is the division of the height to be passed into several small drops



Photo 9: Vertical slot fishpass at Mauzac dam on the Dordogne River (France). (Photo Larinier)



Photo 10: The fishpass at the Iffezheim Dam on the Rhine is one of the most recent vertical slot fishpasses constructed in Europe. Together with the entrance construction, the 37 pools help fish to pass the 10 m high obstacle. (Photo Larinier)



Photo 11: Pool fish pass with triangular weirs at Sarrancolin dam on the Neste River (France). (Photo Larinier)

forming a series of pools. The passage of water from one pool to another is either by surface overflow, through one or more submerged orifices situated in the dividing wall separating two pools, or through one or more notches or slots. Hybrid pool fish passes can often be found, for example with flow through a notch, slot or over the dividing wall combined with submerged flow through an orifice.

The main parameters of a pool pass are the dimensions of the pools and the geometric characteristics of the cross-walls separating the pools (dimensions and heights of the weirs, notches, slots and orifices). These geometric characteristics together with water levels upstream and downstream of the facility determine the hydraulic behaviour of the pass i.e. the flow discharge, the difference in water level from one pool to another, and the flow pattern within the pools.

The pools have a twofold objective: to offer resting areas for fish and to ensure adequate energy dissipation of water, with no carryover of energy from one pool to another. There is throughout the world a large diversity of pool-type fish passes which differ in the dimensions of the pools, the type of interconnection between pools, the differential heads between pools and the flow discharge. Pool length can vary from 0.50 m to more than 10 m, the water depth from 0.50 m to more than 2 m. The discharge can vary from a few dozen l/s to several m³/s and the slope from more than 20% to less than 5%, most frequently ranging from 10% to 12% (Larinier, 1992a, 1998; Bates, 1992; Clay 1995). Design criteria are based on the swimming capacities and behaviour of the species involved as well as hydraulic models and field experience. The drop between pools varies from 0.10 m to more than 0.45 m according to the migratory species, most frequently around 0.30. Pool volume is determined from a maximum energy dissipation in the pools which limits turbulence and aeration. This criterion seems to be commonly accepted nowadays but must be adapted for different species. The maximum values commonly used vary from 200 watts/m³ for salmonids to less than 100 watts/m³ for small species and juveniles (Larinier, 1990; 1992; Bates, 1992; Beitz, pers. comm. 1999).

Pool passes with deep and narrow interconnections, like vertical slot type fish passes, can accommodate significant variations in upstream and downstream water level without the need for regulation sections.

Experience shows that when pool-type fish passes are well designed with respect to the different hydraulic criteria they can allow passage for most species (Travade *et al.*, 1998).

3.3 Denil Fish Passes

The first baffle fish passes were developed in Belgium by a civil engineer, Mr. Denil, for Atlantic salmon. The principle is to place baffles on the floor and/or walls of a rectangular flume with a relatively steep slope (10 to 25 percent), in order to reduce the mean velocities of the flow. These baffles, in shapes of varying complexity, cause secondary helical currents which ensure an extremely efficient dissipation of energy in the flow by intense transfer of the momentum. The Denil concept originated in the 1910s and was later tested with the aim of simplifying the shape of the original baffles, whilst providing a sufficient hydraulic efficiency in the USA in the 1940s, and more recently in the 1980s in France, Canada and Denmark (Larinier, 1992b; Lonnebjerg, 1980; Rajaratnam and Katopodis, 1984).

There is no resting zone for fish in a Denil fish pass, and they must pass through without stopping. When the total drop and consequently the length of the pass become too great, the fish must make an excessive effort for a period which may exceed the limits of its endurance. One or several resting pools should therefore be provided. Practically, resting pools are recommended at 10-12 m intervals for adult salmon and at 6 to 8 m for smaller fish like brown trout or other adult potamodromous species (Larinier, 1992b).



Photo 12: Floor baffles fish pass on the river Thames (UK). (Photo Larinier)

The flow in Denil fish passes is characterised by significant velocity, turbulence and aeration. This type of pass is relatively selective and is really only suitable for species such as salmon, sea-run trout, marine lamprey and large rheophilic potamodromous species such as barbel. Generally, Denil fish passes are used for fish larger than around 30 cm. They may be used for smaller species such as brown trout, on condition that the size of the baffles or slope are reduced significantly.

Three designs of Denil fish passes are now in common use. The first is the “plane baffle” or “standard” Denil fish pass. The width of the baffles usually varies from 0.60 m for brown trout to up to 1.20 m for salmon and sea-run trout. These fish passes are generally operated with slopes of between 15 and 20 percent (Larinier, 1992b). In the second design used (superactive-type baffles), herringbone patterned baffles are placed only on the bottom, while the two sides of the channel are kept smooth. The width of such a design is not limited: several unit-patterns can be juxtaposed according to the size of the river and the discharge required. The baffles are made of thin, prefabricated steel. The maximum slope used is 16 percent. It is mainly used in France and more recently in Great Britain and Japan (Larinier, 1990; Armstrong, 1996; Nakamura, pers. comm., 1999). The third design (Alaska steeppass) is a prefabricated, modular style, Denil fish pass originally developed for use in remote areas. This fish pass has a more complex configuration than the two previous models. The baffles are hydraulically more effective which means that steeper 25-35% slopes can be used (OTA, 1985).

3.4 Nature-like Bypass Channels

The nature-like bypass channel is a waterway designed for fish passage around a particular obstruction which is very similar to a natural tributary of the river. As noted by Parasiewicz *et al.* (1998), the function of a nature-like bypass channel is, to some degree, restorative in that it replaces a portion of the flowing water habitat which has been lost due to impoundment. These channels are characterised by a very low gradient, generally 1 to 5 percent, even less in lowland rivers. Rather than in distinct and



Photo 13: This natural bypass channel has been built on the Gave de Pau to overcome a 5.5 m high dam (Biron dam). The effectiveness of this fish pass has been evaluated to 100% for salmon. (Photo Larinier)



Photo 14: On the Siikajoki River (Finland), one of the fishpasses has been built as an artificial river around the dam; in 20 natural pools (with an approximate drop of $\Delta h = 0,2$ m between two pools) the energy is gently dissipated so that river lampreys, perch and pike can swim upstream to overcome the 4 m-high dam. (Photo Marmulla)

systematically distributed drops as in pool type passes, the energy is dissipated through a series of riffles or cascades positioned more or less regularly as in natural water courses (Gebler, 1998). The main disadvantage of this solution is that it needs considerable space in the vicinity of the obstacle and cannot be adapted to significant variation in upstream level without special devices (gates, sluices). These control devices may cause hydraulic conditions which make fish passage difficult.

As with any other fish pass, it is recommended that the fish entrance to the artificial river be located as close to the obstruction as possible. Given the very low gradient, it is sometimes difficult to position the entrance immediately below the obstruction, which means it must be further downstream. This may restrict their efficiency, and consequently make them less useful for large rivers.

3.5 Fish Locks

A fish lock consists of a large holding chamber located at downstream level of the dam linked to an upstream chamber at the fore bay level by a sloping or vertical shaft. Automated control gates are fitted at the extremities of the upstream and downstream chambers (Travade and Larinier, 1992; Clay, 1995).

The operating principle of a fish lock is very similar to a navigation lock. Fish are attracted into the downstream holding pool which is closed and filled along with the sloping shaft. Fish exit the upstream chamber through the opened gate. A downstream flow is established within the shaft through a bypass located in the downstream chamber to encourage the fish to leave the lock.

The efficiency of such a fish facility depends mainly on the behaviour of the fish which must remain in the downstream pool during the whole of the attraction phase, follow the rising water level during the filling stage, and leave the lock before it empties.

In this respect, it is necessary that the velocity and turbulence in the downstream holding pool be acceptable for the fish. On the other hand, the lock should not be filled up too quickly during the lifting phase, since this would cause excess turbulence and aeration, which might encourage the fish to remain in the lower chamber. The fish should have sufficient time to leave the lock in order to prevent any chance of being swept back downstream when the lock empties.

It is obviously impossible *a priori* to determine the optimum hydraulic conditions for migrating fish. The optimum characteristics of the operating cycle are closely linked to the species concerned. This is why the lock must be designed to have maximum flexibility in its operation (in the duration of each phase of the cycle, the time and extent of opening of the upstream and downstream sluices, etc.).

In spite of these precautions, numerous locks have proved to be either not very efficient, or else totally inefficient. The main drawback of the lock is that it has a limited capacity (in terms of the number of fish which it can handle) compared to that of a traditional fish pass; this is due to the discontinuous nature of its operation and the restricted volume of the lower chamber. The fish attracted into the lock may also leave the downstream chamber before the end of the trapping stage.

The locks constructed at the first dams on the Columbia River (Bonneville, The Dalles, McNary) and elsewhere in the USA were abandoned in favour of pool-type fish passes. Similarly, most locks in France are considered to be ineffective (some of them for obvious design reasons), and certain have been replaced by pool fish passes.

Difficulties due to fish behaviour have been solved in the USA (Rizzo, 1969), in Russia (Pavlov, 1989) and more recently in Australia (Beitz, 1997) by installing a crowder in the holding pool and a follower to coax fish towards the surface of the lock during the filling phase, thus forcing fish to pass upstream.

3.6 Fish Lifts

In fish lifts, fish are directly trapped in a trap with a V-shaped entrance. When the trap is raised, fish and a relatively small quantity of water in the lower part of the trap are lifted up until it reaches the top of the dam. At this point, the lower part of the trap tips forward and empties its contents into the forebay. In order to limit the height of the trap in the case of significant downstream water level variation, and to ensure easier maintenance, the fish lift can be installed upstream from a short section of conventional fish passes.

Where the number of fish to be passed is much larger and can reach hundreds of thousands of individuals, it is no longer possible to hold the fish in the confined volume of the trap. High mortality may occur, especially for Allis shad. Therefore, the design is improved by incorporating a large holding pool into which migratory fish are attracted. A mechanical crowder is used to force fish to enter the area above the tank at the upstream part of the holding pool. The attraction water for the fish lift enters partly at the upstream end of the tank, partly through side or floor diffusers and gratings. Crowder gates at the entrance remain in a V-trap position to prevent fish moving back out through the entrance. Fish collected in the tank are released into an exit channel with low downstream velocities (Travade and Larinier, 1992).

The main advantages of fish lifts compared to other types of fish passage facilities lie in their cost, which is practically independent of the height of the dam, in their small overall volume, and in their low sensitivity to variations in the upstream water level. They are also considered to be more efficient for some species, such as shad, which have difficulty in using traditional fish passes. The main disadvantages lie in the higher cost of operation, and maintenance. Furthermore, the efficiency of lifts



Photo 15: The fish lift at Golfech Dam ($\Delta h = 17$ m) passes thousands of Allis shad (*Alosa alsosa*) each year and has thus helped to restore the shad population of the Garonne River (France) which had been cut off from valuable spawning grounds upstream. (Photo Larinier)



Photo 16: Holding pool and fish crowder at Golfech fish lift on the Garonne river (France). (Photo Larinier)

for small species (e.g. eel) is generally low due to the fact that sufficiently fine screens cannot be used, for operational reasons.

3.7 Navigation Locks

The passage of migratory fish through navigation locks is generally fortuitous, given the low attraction of these facilities, which are located in relatively calm zones to enable boats to manoeuvre. Tests carried out in the USA have shown that less than 1.5% of migrating fish use the lock at the Bonneville dam on the Columbia River (Monan *et al.*, 1970).

However, experiments have shown that navigation locks may constitute a significant back-up facility, or even a useful alternative to the construction of a fish pass at existing sites, providing that their operation is adapted to fish passage. The first condition which must be fulfilled is that a sufficient attraction flow is created in the downstream approach channel to the lock. This can be done by opening the filling sluice of the lock with the downstream gates open. Once the lock is full, it seems necessary to maintain sufficient surface velocity to encourage fish to proceed upstream. More than 10 000 shad passed through the Beaucaire navigation lock on the Rhône river in 1992 in 49 lock operation cycles (Travade and Larinier, 1992). However, the use of navigation locks as fish passage facilities is limited, because the required method of lock operation can be incompatible with navigation requirements.

3.8 Collection and Transportation Facilities

The technique of trapping and transporting migrants is often used as a transitory measure before upstream fish facilities are constructed. For example in the case of a series of dams when the building of fish passes occurs in stages, trapping and transportation can be an interim measure. Fish can be

released upstream on the river in the spawning ground areas or transported to a hatchery, which is often the case for salmonids during the first stage of restoration programmes.

Trapping and transportation can be a more long-term measure in the case of very high dams where the installation of a fish pass would be difficult, or in the case of a series of very close dams intercepting a reach without valuable habitat for breeding.

In the case of dams where suitable entrance conditions are extremely expensive or even physically impossible to obtain, a second dam can be built downstream, which can be low but designed to include optimal entrance conditions. This dam leads the fish to the holding pool, where they can be trapped then transported upstream (Clay, 1995).

Pavlov (1989) describes a floating fish trap used in Russia as part of a system of trapping and transporting fish over dams. It consists of a floating, non-self-propelled barge which is anchored in place. It is supplied by pumps on the end and sides to provide attraction flow. After a period of attraction, a crowder concentrates fish over a lifting device, which then lifts them to the transportation chute of a container vessel. The container vessel is self-propelled and transports fish upstream. This system has the advantage of being able to be placed anywhere in the tailrace, and in the path of migrating fish.



Photo 17: Transport facility at Mactaquac dam on the Saint John river (New Brunswick, Canada). (Photo Larinier)

3.9 Fish Passes for Catadromous Species

Research efforts to adapt fish passes for catadromous species, which enter fresh water and migrate upstream as juveniles, have been much less intense and are relatively recent. Specially designed fish passes for young eels are being developed in Europe, Canada and New Zealand (Porcher, 1992; Clay, 1995; Mitchell, 1995). Research programmes have been recently launched in Australia, Japan and France to design and test fish passes suitable for very small fish.



Photo 18: Young eel fish trap at Piripaua power station on the Waikaretaheke river (New Zealand). (Photo Larinier)

3.10 Location of Fish Passes

For a fish pass to be considered efficient, the entrance must be designed so that fish find it with a minimum of delay as “No fish in = No fish out” (Bates, 1992). The width of the entrance is small in proportion to the overall width of the obstacle and its flow represents only a limited fraction of the total river flow. The only active stimulus used to guide the fish towards the entrance is the flow pattern at the obstruction. The attraction of a fish pass, i.e. the fact that fish find the entrance more or less rapidly depends on its location in relation to the obstruction, particularly the location of its entrance and the hydraulic conditions (flow discharges, velocities and flow patterns) in the vicinity of these entrances. The latter must neither be masked by the turbulence due to the turbines or the spillway, nor by recirculating zones or static water.

In a case of a wide river it may be necessary to provide not only several entrances but also more than one fish pass because a single fish pass cannot be expected to attract certain species from the opposite bank. Migrating fish may arrive either at the bank where the powerhouse is located or at the opposite bank where the spillway is discharging and it is therefore advisable to design two separate fish passes, each with one or more entrances.



Photo 19: General view of Ice Harbor dam on the Columbia river showing the first fish pass and the collection gallery at the powerhouse and the second fish pass at the spillway. For a flow of $2800 \text{ m}^3/\text{s}$ in the river, the flow at the different entrances of the upstream fish facilities represents 2.6% of the river discharge (i.e. $72 \text{ m}^3/\text{s}$). (Photo Larinier)



Photo 20: Collection gallery above the turbine drafttubes at Mactaquac powerhouse (Saint John river, Canada). (Photo Larinier)



Photo 21: Introduction of auxiliary water through lateral screens at Iffezheim fish pass (river Rhine). Auxiliary flow is supplied from forebay through a special turbine (fish pass discharge 1.2 m³/s, turbine discharge 12 m³/s). (Photo Larinier)

The siting of the pass entrance at an obstruction is not the only factor to be taken into account when positioning a fish pass. The exit of the fish pass should neither be situated in a fast flowing zone near a spillway, weir or sluice, where there is a risk of the fish being swept back downstream, nor in a static area, or recirculating zone in which the fish could become trapped.

Finding the best position for entrances to the fish pass where there are turbines is not easy and rarely obvious. The hydraulic barrier to the fish may be at the exit of the draft tubes, upstream of a zone of boiling water caused by the large turbulent eddies resulting from turbine discharges. On the other hand when the residual energy from the water leaving the turbine is significantly great, the hydraulic barrier to the fish may occur further downstream. Finally the location of the hydraulic barrier can vary within the same site, depending upon exactly which turbines are in use at any one time.

When, in a particular site, the blockage zones cannot be clearly identified and are likely to vary depending on plant operating conditions, meaning that the correct fish pass entrance locations are not obvious, then effectiveness will be considerably improved by installing several entrances at points which appear, *a priori*, to be the most favourable. The problem is extremely complicated and difficult to solve in the case where the fish passage facility is intended for several species whose swimming abilities and migratory behaviour are very different, or sometimes even unknown. If the pass is intended primarily for migratory salmonids then the entrance should be as far upstream as possible and relatively close to the turbines. On the other hand, this may not be favourable for smaller fish which do not have the same swimming ability. For these species it is better to position the entrance to the fish pass further downstream, in a calmer and less turbulent zone. This gives rise to the necessity to define the target species clearly at the outset of the project.

The discharge through the fish passage facility must be sufficient to compete with the flow in the river during the migration period. It is difficult to give precise criteria, but generally the flow passing

through the fish pass must be of the order of 1-5% of the competing flow. It is clear that the higher the percentage flow of the water course passing through the fish pass, the greater the attraction of the pass will be. Although it is reasonably possible to direct a large fraction of the flow of the river through the fish pass in the case of small rivers, this is not the case in large rivers where the mean flow can exceed several hundred m³/s. It then becomes difficult, in terms of cost, to maintain a sufficient flow through the facility, particularly during high water periods. On major rivers an attraction flow of around 10% of the minimum flow of the river (for the lower design flow), and between 1 and 1.5% of the higher design flow seem to be satisfactory for a well located fish pass to work.

Generally, although it may be demonstrated that an increase in attraction flow generally results in improved efficiency, it is very difficult to quantify the benefit at each site, either in terms of an increased percentage of migrants passing, or a reduction in the migration delay. It is evident that part of the improvement in efficiency is a function of the higher number of entrances usually made possible by the increased availability of flow for the fish pass in these circumstances.

When a large flow of water is needed to attract fish into a fish pass (several m³/s) only a fraction should be allowed through the fish pass itself in order to limit the size and the cost of the facilities. The auxiliary flow needed for attraction is then injected at low pressure and velocity through screens in the downstream section of the pass, or at the entrance itself. The auxiliary flow (or supplementary attraction flow) is fed either by gravity after dissipation of the energy in a pool, or, in large installations either by pumping from the downstream pool or taking discharge after passage through one or several small special turbines in order to reduce energy losses (Bates, 1992; Larinier, 1992).

3.11 Effectiveness and Efficiency of Upstream Fish Facilities

The answer to the question “are fish passes effective mitigation means” is not obvious. The biological objectives of building a fish pass vary according to site, and even on the same site depending on the species considered. The concept of effectiveness is therefore very variable and can only be defined with respect to an objective.

The concepts of effectiveness and efficiency may be used to clarify the degree of mitigation provided by a fish pass.

Effectiveness is a qualitative concept which consists in checking that the pass is capable of letting all target species through within the range of environmental conditions observed during the migration period. Effectiveness may be measured through inspections and checks: visual inspection, trapping, video checks (Travade *et al.*, 1998).

The efficiency of a fish pass is a more quantitative description of its performance. It may be defined as the proportion of stock present at the dam which then enters and successfully moves through the fish pass in what is considered an acceptable length of time. The methods giving an insight into the efficiency of a pass are more complicated than those for effectiveness. Marking and telemetry are valuable techniques to assess the overall efficiency of fish passes and the cumulative effect of various dams along a migration path.

The targeted effectiveness for a given site must be defined with respect to the biological objectives sought. It is therefore related to the species considered, the number of obstacles on the river and the position of the obstacle on the migration route.

In a pass designed for diadromous species such as salmon and located downstream of all the spawning grounds, the objective is to move the whole migrating population through. If this river is marked by numerous obstacles, the aim is to minimize the time taken by the fish to enter the pass, so that the



Photo 22: Allis shad pass the counting chamber at Tuilières fish lift on the Dordogne river (France). (Photo Larinier)

migrating fish reach the reproduction areas on time. The efficiency of a fish pass is expressed both in terms of the *percentage* of the population which clear the obstacle and the *migration delay*, i.e. how long the population, or part of the population, takes to clear the obstacle. On the other hand, if the pass is located upstream of the river in the spawning grounds, the requirements on percentage and time taken may be less stringent seeing that the fish may reproduce downstream and that the motivation to migrate may be variable. Whatever the case, the fish pass must be sufficiently efficient so as not to constitute a limiting factor in the long-term maintenance of migrating stock.

When dealing with a fish pass for potamodromous species, whose biological objective is above all to avoid the sectorisation of populations in the various reaches, it is not necessary to seek to move all the populations downstream of an obstacle. The pass will be effective if a “certain number” of individuals, i.e. a significant proportion with respect to the population downstream of the obstacle, gets through the pass. The objective of a fish pass may be more ambitious and may consist in providing a passage for all species at every stage in the river and for all individuals wishing to clear the obstacle. If no goal is set, there can be no real measure of effectiveness.

When the causes of poor performance (in terms of effectiveness and/or efficiency) of fish facilities are analysed, certain factors are frequently revealed (Larinier *et al.*, 1992; Nakamura, 1993; OTA, 1995):

- Lack of attraction of the facility, resulting from a poor position of the fish pass or insufficient flow at the entrance of the facility in relation to the flow discharge into the river.
- Poor design of the facility with regard to the variations in water levels upstream and downstream during the migration period, resulting in under or oversupply of flow to the fish pass, or

excessive drop at the entrance. This may be due to poor appreciation of the range of the upstream and/or downstream water levels during the project planning phase, or a subsequent change in these levels.

- Poor dimensions : pools with insufficient volume causing excessive turbulence and aeration, excessive drop between pools, insufficient depth for the fish, or the flow pattern in the pools not suitable for the target species.
- Frequent clogging up or obstruction of the fish passage facility, resulting from inadequate protection against debris, or too exposed a position, or quite simply inadequate maintenance on the part of the operator.
- Malfunctioning of parts which regulate the flow discharge and the drops between pools (automatic sluice gates, etc.), or which ensure the functioning of the facility in the case of fish lifts and fish locks (automatic sluice gates, hoist for the tank, moving screens, etc.).

However, there are limits to the effectiveness of a fish pass. Even when 100 % effective, a pass may prove insufficient for maintaining the balance of a migratory population in the long term. As previously pointed out, in addition to problems arising from fish passage there are indirect effects such as a change in hydrological regime, water quality, an increase in predation and the loss or deterioration of the habitat upstream or downstream which may also be limiting factors. These aspects are however species- and site-specific. Other mitigation measures, for example on specific water flow management for fish at certain times of the year, may prove indispensable.

4. DOWNSTREAM FISH PASSAGE FACILITIES

Downstream fish passage technologies are much less advanced than those concerning upstream fish passage facilities and are the areas most in need of research. This is obviously partly due to the fact that efforts towards re-establishing free movement for migrating fish began with the construction of upstream fish passage facilities and that downstream migration problems have only more recently been addressed. This is also because the development of effective facilities for downstream migration is much more difficult and complex. As yet, no country has found a satisfactory solution to downstream migration problems, especially where large installations are involved (EPRI, 1994). As a general rule, problems concerning downstream migration have been thoroughly examined in Europe and North America with regard to anadromous species, and more particularly to salmonids. Comparatively little information is available on other migratory species.

A large number of systems exist to prevent fish from being entrained into water intakes, although they are by no means equally effective. They may take the form of physical barriers which physically exclude fish from turbine intake or behavioural barriers which attract or repel them by means of applying sensori stimuli to elicit behavioural responses. Both types are associated with bypasses for downstream passage.

The design of effective facilities for assisting the downstream passage of fish must take into account the limited swimming ability and behaviour of the target species, and the physical and hydraulic conditions at the water intake.

4.1 Physical Barriers

One solution to prevent fish from passing through the turbines involves stopping them physically at water intakes using screens which must have a sufficiently small mesh to physically prevent fish from passing through. These screens have to guide fish towards a bypass, which is done most effectively by placing them diagonally to the flow, with the bypass in the downstream part of the screen.

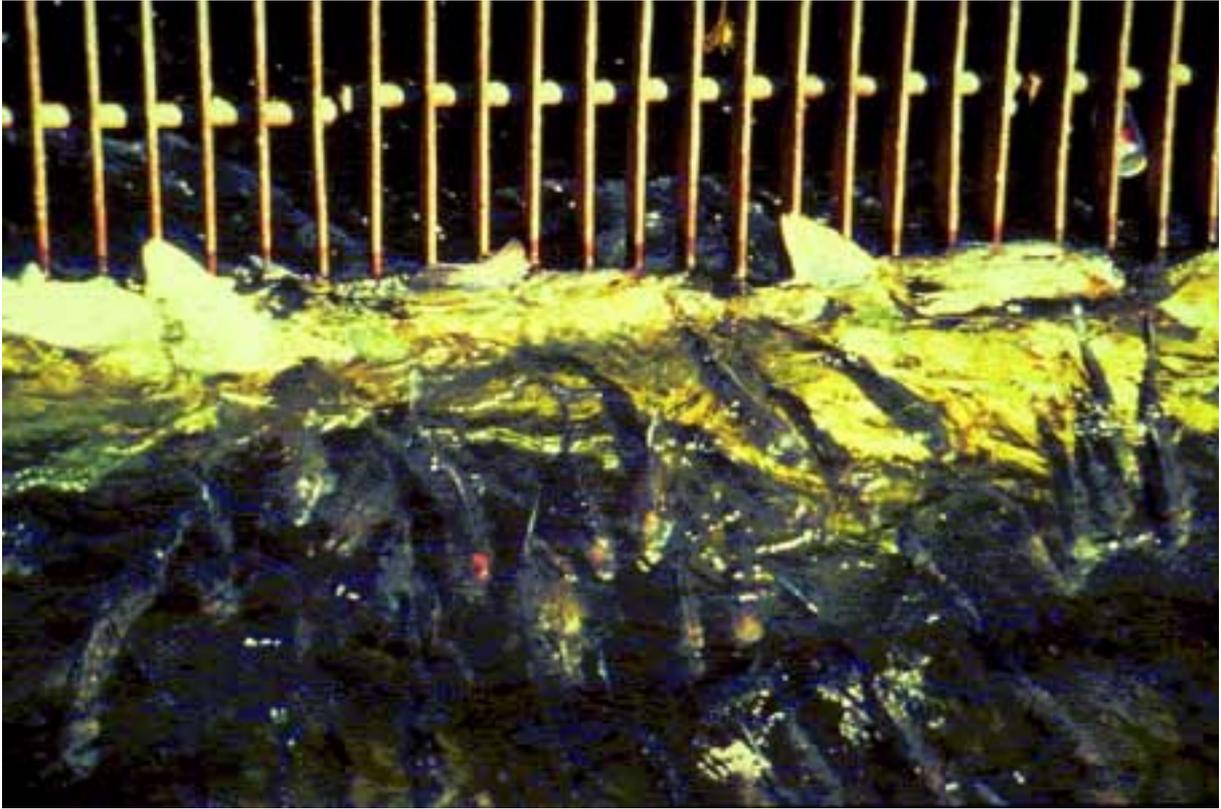


Photo 23: Impingement of downstream migrating adult American shad at a powerhouse intake. (Photo Larinier)



Photo 24: Fine mesh screen at an hydroelectric power plant intake on the Loch Ness in Scotland. (Photo Travade)

Sufficient screen area must be provided to create low flow velocities to avoid fish impingement. The velocity of the flow towards the screen should be adapted to suit the swimming capacities of the species and stages concerned. Physical screens can be made of various materials: perforated plates, metal bars, wedgewire, plastic or metal mesh. Uniform velocities and eddy-free currents upstream of screens must be provided to effectively guide fish towards the bypass (ASCE, 1995; Larinier and Travade, 1999).

4.2 Behavioural Barriers

Visual, auditory, electrical, and hydrodynamic stimuli have resulted in a large number of experimental barriers: bubble screens, sound screens, fixed and movable chain screens, attractive or repellent light screens, electrical screens and hydrodynamic ('louver') screens.

Results obtained in particular cases with various screens (visible chain, light and sound screens) have not been of any great use because of their specificity (efficiency as a function of species and size), low reliability and their susceptibility to local conditions (water turbidity, hydraulic conditions).

The hydrodynamic or 'louver' screen consists of an array of vertical slats aligned across the canal intake at a specified angle to the flow direction (ASCE, 1995) and guide fish towards a bypass. It has been used with some success in several sites, namely on the east coast of the USA: Louvers may be considered for sites with relatively high approach velocities, uniform flow and relatively shallow depths. The efficiency is highly dependent on the flow pattern in the canal intake (ASCE, 1995). The first louvers were installed over the full depth of the approach channel. However, more recently, several 'partial-depth' louver systems have been installed in the USA, based on the observation that migrating Atlantic salmon smolts and juveniles clupeids remained in the upper portion of the water column. The partial-depth system recently installed in the intake channel of the Holyoke hydroelectric power station on the Connecticut River has an efficiency of 86% for juvenile clupeids and 97% for Atlantic salmon smolts (Odeh and Orvis, 1998).

The use of behavioural barriers, which are still experimental, must be considered with caution (OTA, 1995).

4.3 Surface Bypasses Associated to Surface Bar Racks or Deep Intakes

Surface bypasses associated with existing conventional trashracks or angled bar racks with relatively close spacing have become one of the most frequently prescribed fish protection systems for small hydroelectric power projects, particularly in the Northeast of the USA and in France. These structural guidance devices act as physical barriers for larger fish (downstream migrating adults) and behavioural barriers for juveniles. The efficiency is closely related to fish length to spacing ratio and to fish response to hydraulic conditions around the front of the structure and at the bypass entrance. Tests showed that under optimal conditions, efficiency can reach 60-85% (Larinier and Travade, 1999). Flow discharge in the bypass has also been proven to be critical. The design criteria currently applied in the USA and France call for a minimum discharge of 2% to more than 5% of the turbine discharge (Odeh and Orvis, 1998; Larinier and Travade, 1998).

In the Columbia River Basin, there is a major effort under way to develop surface bypasses associated with relatively deep water intakes. Various design configurations are being evaluated. The volume of bypass flow required to be sufficiently attractive is thought to lie in the 5% to 10% range. The design goal of these bypasses is to guide at least 80% of the juvenile fish (Ferguson *et al.*, 1998).

4.4 Eels

The problem of the downstream migration of eels (*Anguilla* spp.) at hydroelectric power stations is critical in the light of their size and the numerous fatalities which result. No specific solution has been implemented in North America or Europe due to the relatively recent awareness of eel migration. Only physical barriers are likely to work, but their installation would mean redesigning most water intakes (increase in the surface area of the filter due to smaller grid spacing). Due to the demersal behaviour of the species, there is no certainty that the approach used for juvenile salmonids with surface bypasses combined with existing trashracks would be efficient. Experiments on bottom bypasses need to be undertaken, although it must be recognised that even if this technique were to prove efficient, there would be a considerable challenge to design facilities that did not create significant maintenance problems. The principle of behavioural light screens appears promising, taking into account the species repulsion to light (Haddington *et al.*, 1992). Stopping turbines during downstream migration is a solution already envisaged, as is the capture of individuals upstream of the obstacles for *Anguilla rostrata* in the USA (Euston *et al.*, 1998) and *Anguilla dieffenbachi* in New Zealand (Mitchell, 1995). However, these solutions assume that the downstream migration period is both predictable and sufficiently short, which does not appear to be the case for the European eel (*Anguilla anguilla*) if we consider downstream migration monitoring (Larinier and Travade, 1999).

5. FISH PASSES AROUND THE WORLD

The following review is not considered exhaustive. It aims to explore the current use of fish passes throughout the world, the target species, the state of technology and the current philosophy. Some countries are not mentioned because the state of the art is poorly documented or unscientific and some because they are of no great interest within the framework of this limited document.

5.1 North America

There are about 76 000 dams in the USA, about 2 350 operating hydroelectric projects and only 1 825 are non-federal projects licensed by the FERC (Federal Energy Regulatory Commission) (Cada, 1998). Upstream facilities and downstream passage technologies are respectively in use at 9.5 and 13 percent of the FERC-licensed hydropower plants (OTA, 1995). Fish passage requirements are most common along the Pacific and Atlantic coast which support the most important anadromous fisheries and in the Rocky Mountains which have valuable recreational fisheries.

The main advances in upstream passage technology have come from the west coast of USA and Canada, where fish passage facilities have gradually become more sophisticated over the years since the building of the first dam (Bonneville dam) about 60 years ago on the Columbia river (OTA, 1995). Currently, about 40 large-scale hydro developments are in place on the Columbia river. Upstream passage technologies are considered to be well-developed and understood for the main anadromous species including salmonids (Pacific salmon and steelhead trout), and clupeids (American shad, alewife and blueback herring, *Alosa* spp.), as well as striped bass (*Morone saxatilis*). Upstream passage fish facilities have not been specifically designed for potamodromous species, although some of these fish will use them (carp, northern squawfish, suckers, shiner, whitefish, chub, dace, crappie, catfish, trout...). Most of these fish passes are pool-type fish passes with lateral notches and orifices (Ice Harbor type pool fish pass), or vertical slot pool fish passes where it is necessary to accommodate higher upstream and downstream variations in water levels (Clay, 1995).

For smaller facilities, vertical slot fish passes are the most frequent type of design in British Columbia and pool and weir fish passes in Washington and Oregon (Walburn and Gillis, 1985). The Denil fish pass is not widely used in the West coast, except in Alaska for salmon (*Oncorhynchus* spp.) where its

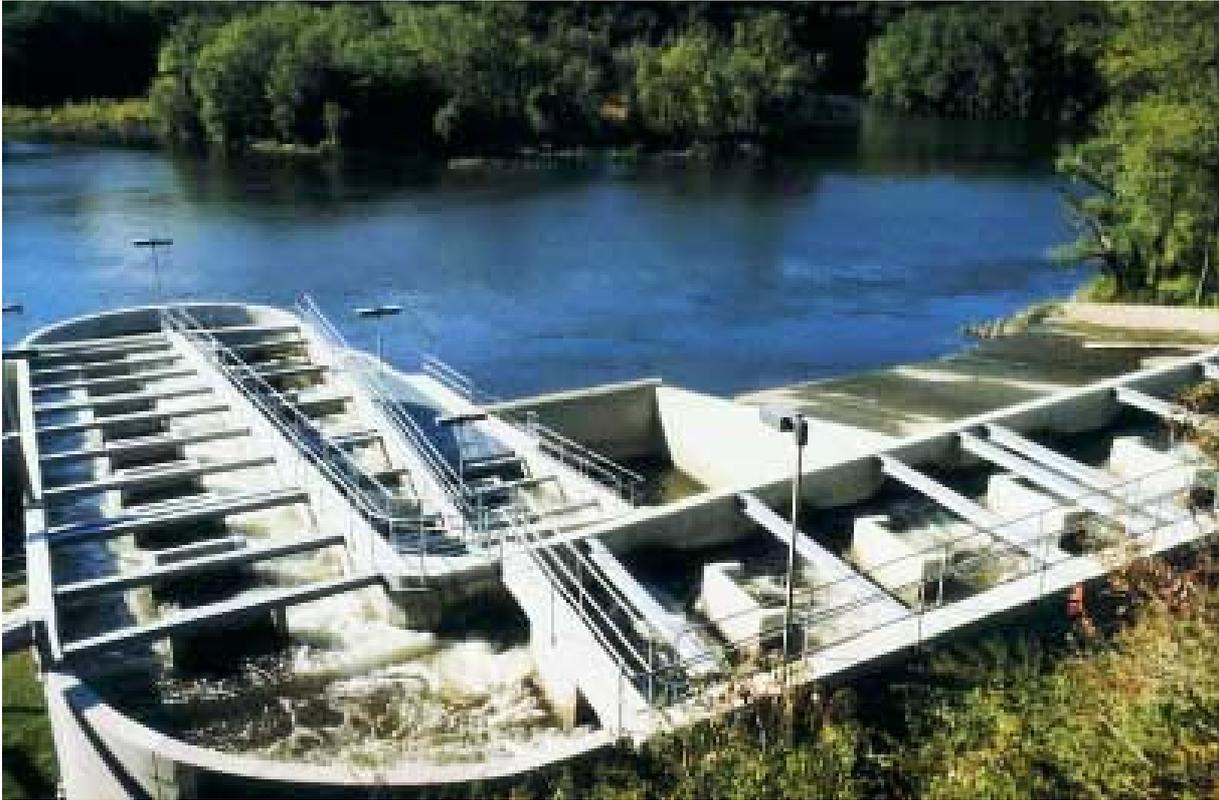


Photo 25: Ice Harbor-type pool fish pass at Turner Falls on the Connecticut River. (Photo Larinier)

light weight and mobility when constructed of aluminium, have proven useful for installations at natural obstructions that are inaccessible except by helicopter (Ziemer, 1962; Clay, 1995).

On the East coast of the USA and Canada, the advances in fish pass design are more recent, since anadromous species restoration programs on the main rivers of New England (Connecticut, Merrimack, Penobscot, St Croix river) were launched in the sixties of the last century. Fish passes of all types have been used to pass the following target species, Atlantic salmon (*Salmo salar*), shad (*Alosa sapidissima*), alewife (*Alosa pseudoharengus*), striped bass (*Morone saxatilis*), smelt (*Osmerus mordax*) and sea-run brook trout (*Salvelinus fontinalis*). Fish lifts have been successfully used to pass large populations of shad on the Connecticut, Merrimack and Susquehanna rivers. Denil fish passes have been used in Maine, namely for salmon and alewife. Fish pass development in the Maritimes appears to have followed the Maine experience closely with the exception that Denil fish passes were not widely constructed (Washburn and Gillis, 1985). For the same species, pool and weir fish passes are preferred, with drops varying from 0.15 m for smelt and up to 0.60 m drop for salmon (Conrad and Jansen, 1983). In the East coast of Canada, Clay (1995) reported there are 240 fish passes.

For central Canada and the USA, Clay (1995) lists 40 fish passes used by potamodromous species as catostomids, cyprinids, ictalurids, esocids , gadids and percids, as well as salmonids such as *Salvelinus*, *Coregonus*, *Thymallus* (Schwallme, 1985).

Francfort *et al.* (1994) completed a detailed study of the benefits and costs of measures used to enhance upstream and downstream fish passage at dams using operational monitoring studies data from 16 cases study projects across the USA which represent the measures most commonly used in the USA. At least six of the case study projects have successfully increased the upstream passage rates or downstream passage survivals of anadromous species. The most significant success are the two fish lifts at the Conowingo dam which are an essential part of the Susquehanna river shad restoration

programme: adult shad numbers below the dam increased from 4 000 to over 80 000 between 1984 and 1992 (Cada, 1998). Although all of the projects had conducted some degree of performance monitoring of their fish passage mitigation measures, there were substantial differences in the extent and rigour of the studies : for some projects monitoring was limited to studies during a single season or based only on visual observations. For most case study projects benefits could be expressed only in terms of the increased numbers of fish transported around the dam. The influence of these increased numbers on the subsequent size of the fish populations was rarely known (Cada, 1998).

5.2 Europe

In England and Wales, a recent inventory suggests that there are approximately 380 fish passes. More than 100 have been built since 1989 (Cowx, 1998). For many years fish passes have been built almost exclusively for Atlantic salmon and sea-run brown trout. The awareness of the need for the passage of potamodromous species ('coarse' fish) and other non-salmonid diadromous species such as shad (allis and twaite) or eel is more recent. The most commonly used fish pass is the pool-type fish pass (Beach, 1984) in England and Wales, and more recently floor baffle Denil fish passes (Armstrong, 1996). In Scotland, submerged orifice fish passes, pool and weir passes and fish locks were used in the fifties of the last century.

In France, recent legislation, adopted in 1984, requires that free passage must be assured through all obstructions situated on designated 'migratory fish' rivers. The diadromous species considered are Atlantic salmon, sea-run brown trout, sea lamprey, Allis shad, and eel. The only potamodromous species taken into account by the law are brown trout, northern pike and European grayling. Consequently, more than 500 fish passes have been built or retrofitted over the last 17 years. As a result of experience gained, in particular from experiments with hydraulic models, and on-site monitoring, certain advances have been made in the choice and design criteria for upstream fish facilities. Denil

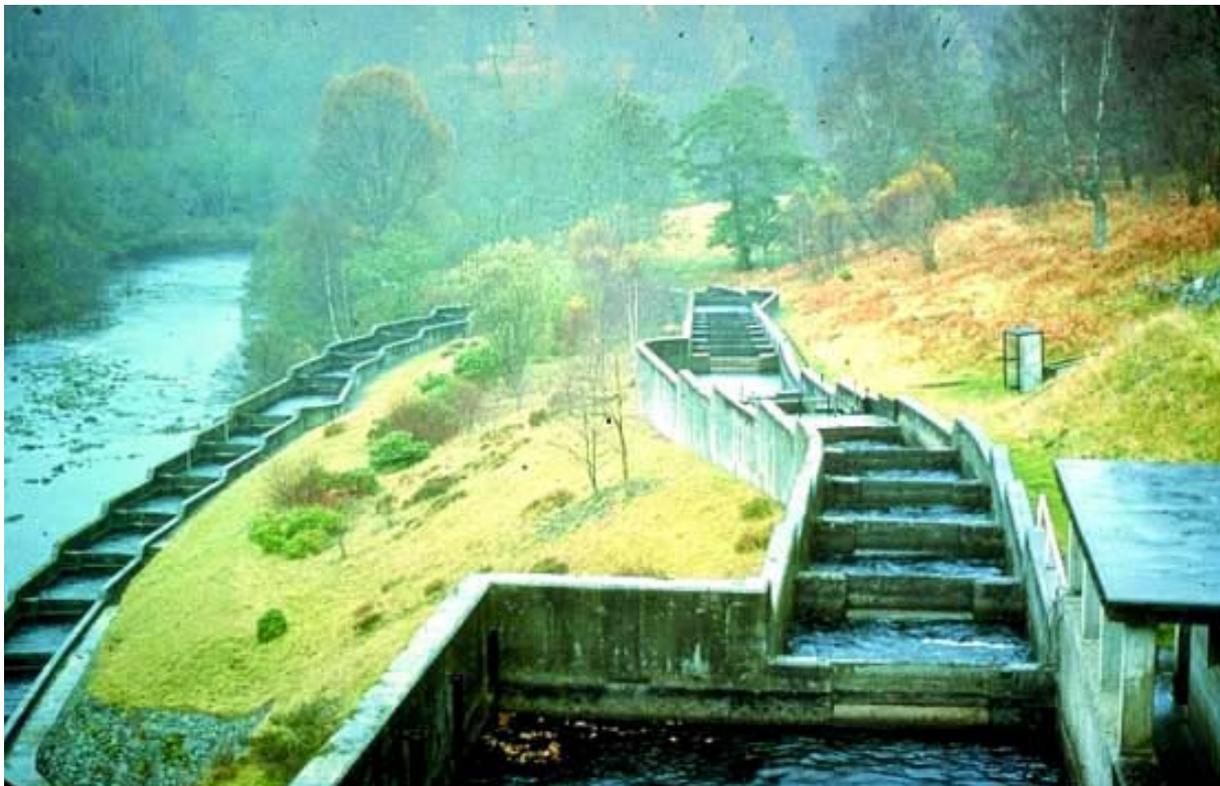


Photo 26: Submerged orifice fish passes at Clunie dam in Scotland. (Photo Larinier)



Photo 27: Due to the fish lift at the Tuilières Dam on the Dordogne River (France), migratory species such as salmon and Allis shad can now pass the obstacle and reach spawning grounds that are situated further upstream. (Photo Larinier)

fish passes are only used for Atlantic salmon, sea-run brown trout and sea lamprey on small rivers. Fish lifts or large pool-type passes with large and deep passages (vertical slot or deep notches) are used for shad. When several species must be taken into account, the recommended fish pass is the pool type (Larinier, 1998).

In Germany and Austria, design and construction of fish passes has also been very active over the last 15 years. Fish pass design tends to take into consideration many of the potamodromous species (brown trout, cyprinids, percids, etc.). The most common fish pass used is the natural-like bypass channel (Parasiewicz *et al.*, 1998). However, where land is limited, more conventional pool and weir fish passes are used (DVWK, 1996).

Pavlov (1989) reviewed fish passes in the former USSR. Conventional pool and weir fish passes are used for salmonids. He describes fish facilities built in the Caspian basin, Azov and Black seas, and in particular on the Volga, Don and Kuban rivers where target species were Acipenseridae, Clupeidae, Cyprinidae, namely *Vimba vimba*, Percidae and Siluridae. Very large fish locks, fish sluice, fish lifts and mobile devices for fish collection and transport have been designed for these species.

5.3 Asia

There are probably about 10 000 fish passes installed on Japanese rivers (Nakamura and Yotsukura, 1987). They are mainly designed for anadromous salmonids (*Oncorhynchus* spp.), Japanese eel, gobies (*Rhinogobius* spp.), and the ayu (*Plecoglossus altivelis*) which is a very valuable amphidromous species whose juveniles (50-60 mm long) migrate upstream. Recently, riverine species have also been selected as target species (Nakamura, 1993). Over 95 percent of fish passes are conventional pool and weir fish passes, the others are vertical slot and Denil type. Most of the first fish passes designed for ayu were not efficient because they were imitations of European designs which were only suitable for larger fish

(Nakamura *et al.*, 1991). Following the two Symposia on fish passes held in Gifu in 1990 and 1995, a large effort is being made to improve and adapt fish pass design to Japanese species: 'the improvement of fish passes is progressing so rapidly that it is known as a fishway revolution' (Nakamura, 1993).

As noted by Wang (1990) and Clay (1995), China has a vast system of reservoirs (about 86 000) and the fisheries of these reservoirs are intensively exploited and maintained by stocking from hatcheries, so that little need has been felt for fish passes.

The first fish passes are only 40 years old (Wang, 1990) and around 60 to 80 fish passes have been built (Nakamura, 1993). The main target species are potamodromous species, mainly four species of carp, and catadromous species, mainly Japanese eel. Most fish passes are pool-type.

Zhili *et al.*, (1990) describe the Yangtang fishway on the Mishui river, which pass 45 species and more than 580 000 fish per year. The fish pass effectiveness was fairly well monitored (5 000 hours of observation annually). The effect of the fish pass seems to be significant, statistics of fish harvest showed that the annual fish output in the upstream part of the Mishui river increased to 3.5 times compared with that in the years before the fishway building. This fish pass has been specifically designed to pass very small fish, with very low turbulence in pools and low drops (about 0.05 m) between pools. The attraction flow (16 m³/s) and the collection gallery above the turbines are considered to play an essential role in the effectiveness of the facility. This fish pass is one of the few examples of a well designed fish pass, adapted to native species and well monitored in developing countries.

5.4 Africa

Africa has over 2 000 known species of indigenous freshwater fishes. The construction of dams has multiplied since the 50s for both irrigation and hydroelectric power generation.

Shad populations are present in North African rivers, namely in Morocco, but the existing and (for some of them) recent fish passes seem not adapted to this species. Shad disappeared from the Oum-er-Rbia after the construction of the Sidi-Saïd dam, equipped with a Denil-type fish pass (Chapuis, 1963). The fish pass planned in 1991 on the Garde dam on the Oued Sebou was neither adapted to shad, nor to the dam and was clearly bounded to fail (Larinier, pers. comm., 1991).

Apart from shad in North Africa, no anadromous species are known. As noted in Daget *et al.* (1988), dams are only likely to hinder potamodromous species such as large Labeo, Barbus, Alestes, Distichodus and Citharinus which migrate long distances up and down rivers in relation to their breeding cycle and seasonal flooding. The impact of dams is perhaps more obvious in the disappearance of biotopes for some rheophilic species located in areas where there are rapids, gorges or rocky ground, all of which are areas likely to be chosen for dam building.

In South Africa, the need for fish passes has become apparent only in recent years. This country has a low diversity of freshwater fish. In the coastal streams there are only six catadromous species: striped mullet, freshwater mullet and four species of eels (Mallen-Cooper, 1996). In the more inland rivers of the Transvaal, there are potamodromous species, mainly cyprinids, with both juveniles and adult migrating upstream. The few existing fish passes (only 7 in 1990, Bok, 1990), have been based on existing European and North American designs for salmonids and do not meet the needs of native species.

5.5 Australia

In temperate south-eastern Australia, there are approximately 66 indigenous freshwater species; over 40% of these make large-scale movements or migrations that are essential for the completion of their

life histories (Mallen-Cooper and Harris, 1990). Coastal streams have many migratory fishes that are catadromous or amphidromous, with both juveniles and adults migrating upstream. In the second major drainage system, the Murray-Darling river system, most migrating species are potamodromous with adults migrating upstream. About 50 fish passes have been recorded (Mallen-Cooper and Harris, 1990). Most of them are pool-type fish passes and were judged ineffective because inadequate maintenance and inappropriate design characteristics, i.e. steep slopes, velocities and turbulence were not adapted to native species.

In New South Wales, up to mid-1980's salmonid pool-type designs (submerged orifice and pool-and-weir) with salmonid design criteria were used. Recent laboratory studies on native fish using experimental vertical-slot fishways showed successful. Field studies on these vertical-slot fishways (with reduced head losses between pools and reduced turbulence compared with salmonid fishways) have confirmed effectiveness for native fishes (Mallen Cooper, pers. comm., 2000). Rock ramps and nature-like bypass channels with very low slope (1:20 to 1:30) are used on smaller barriers. Their use is still experimental. They have had some initial success in passing fish and assessment in most cases is continuing (Mallen Cooper, pers. comm., 2000).

In the state of Queensland, a tropical and sub-tropical region of Australia, about 22 fish passes were built prior to 1970, most of them on tidal dams (Barry, 1990). Early designs were based on fish passes used for salmon and trout in the northern hemisphere. The majority of these fish passes were judged to be ineffective in providing native fish passage, mainly striped mullet (*Mugil cephalus*) and barramundi (*Lates calcarifer*) (Beitz, 1997) which support important commercial fisheries.

Under the guidance of a Fish Pass Coordinating Committee, Queensland has begun a programme of fish pass design, construction and monitoring which better reflects the requirements of native fish. A major programme of retrofitting existing fish passes has been launched (Jackson, 1997). The actual philosophy in Queensland is to use locks where dam heights exceed 6 metres and vertical slot fish passes elsewhere with 0.08 to 0.15 m drop heights between pools (Beitz, pers. comm. 1999).

5.6 New Zealand

Of the currently recognised 35 indigenous freshwater fish species in New Zealand, 18 are diadromous. The species that require passage to and from the sea are the three eel species (*Anguilla* spp.), one lamprey (*Geotria australis*), five galaxiids (*Galaxias* spp.), two smelts (*Retropinna* spp.), four bullies (*Gobiomorphus* spp.), the torrentfish (*Cheimarrichthys fosteri*), grey mullet (*Mugil cephalus*) and black flounder (*Rhombosolea retiaria*). There is also one shrimp (*Paratya curvirostris*) which require passage, and numerous marine wanderers have been affected by structures built in the lower reaches of waterways. Of the diadromous species, galaxiids (whitebait) and eels support important commercial, recreational and traditional fisheries. In addition to the indigenous species there is at least one species of the introduced salmonids that that do require passage to and from the sea. Other introduced species that have formed land locked populations, notably the introduced brown and rainbow trout and can also undertake extensive migrations within river systems (Boubée, pers. comm., 2000).

The 1947 fish pass regulation gave fisheries authorities the right to require a fish pass on any dam or weir built on rivers where trout or salmon did or could exist. No provision was made for passage of indigenous species, quite the contrary. Indeed, fisheries managers at that time advocated exclusion of elvers as beneficial to upstream population of introduced trout. By the early 1980s, only around eight fish passes had been built at the 33 or so major power, water and flood control dams scattered around the country. All eight passes had been constructed for salmon which, although introduced, were considered the most economically valuable fish species (Jowett, 1987).

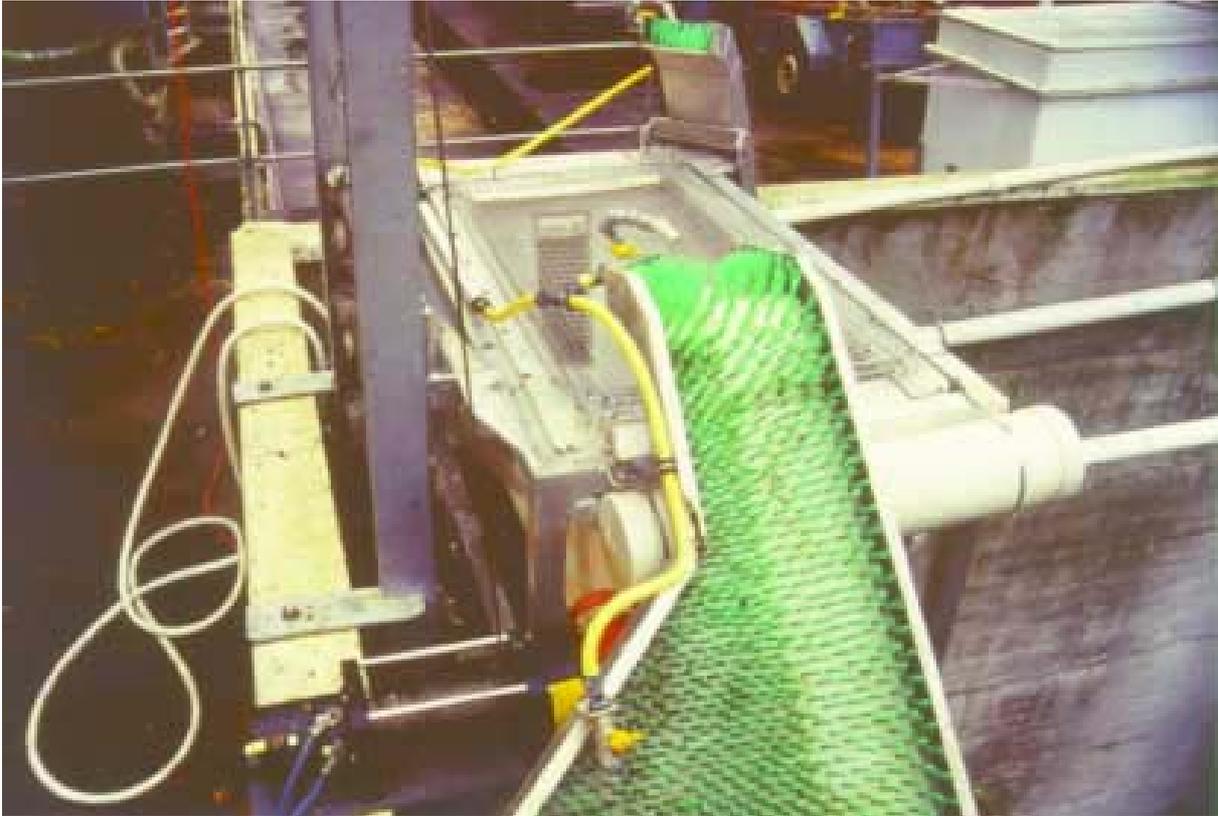


Photo 28: Elver trap at Karapiro dam (New Zealand). This floating trap is periodically raised to pass the small eels upstream. (Photo Larinier)

Only with the introduction of the 1983 Freshwater Fisheries regulation did passage of indigenous fish species become a requirement for new structures.

Although several fish passes have been built since the 1980s, numerous migration barriers remain, not only at high dams but also at weirs, culverts and flood gates. Passage upstream for the climbing native species has been aided by placing pipes or ramps lined with gravel or brushes over the barrier (Mitchell, 1990; 1995). Although some success has been achieved at high dams these type of passes have proven to be far more effective at low head structures. More successful for high structures are catch and haul operations where elvers, climbing galaxiids and bullies are collected via short ramps into holding bins, and transported upstream by road. Such operations have been particularly valuable in systems with one or more dam or where passage or access would be limited because of flow diversion (Boubée, pers. comm., 2000).

With the increasing success of fish passes and of transfer operations, downstream passage, notably of adult eels now needs to be addressed. So far there are no downstream passage facilities installed at any of the power dams.

5.7 Latin America

As noted by Northcote (1998), with possibly some 5000 species of freshwater fishes in South America and probably more than 1300 in the Amazon Basin (Petrere, 1989), the potential for fish passage problems at dams is enormous. Fish communities in the large rivers comprise mainly potamodromous characins and siluroids. Among the characins, prochilodids of the genera *Semaprochilodus* and *Prochilodus* make up a large proportion of the catches. The siluroids include *Pimelodus*, *Brachyplatystoma*, *Pseudoplatystoma* and *Plecostomus*. Fish can migrate distances from 200 to 1 000 km (Welcomme, 1985).

Hydroelectric impoundments are seen as potentially the most dangerous human threat to Amazonian fisheries (Bayley and Petrere, 1989). In Brazil, Petrere (1989) recorded about 1 100 dams, which include only dams owned and managed by the Central Government. Dam construction in the upper reaches of rivers appears to lead to the disappearance of migratory stocks in reservoirs and in the river upstream. Most dams have no facilities for fish passage (Quiros, 1989). He listed for the whole of Latin America only 46 fish passes with another 7 planned or under construction. Itaipu Dam, on the Parana River, was built without fish facilities for upstream migration, except for an experimental model, which was installed to obtain more precise information on the biology of the migratory species attracted to the structure. The attracting flow was only 0.3 m³/s when the average river flow-rate during the experiment was 11 800 m³/s (Borghetti *et al.*, 1994). The recently built Petit Saut dam on the Sinnamary (French Guiana) has no fish passage facilities.

The first fish passes built were pool and weir types, used in the northern hemisphere for passing salmonids. More recently, fish locks and mechanical fish lifts based on Russian experience described by Pavlov (1989) have been built for obstacles over 20 m in height.

Very few fish passes have been evaluated and they seem to function with varying degrees of success. Quiros (1989) mentions 3 ineffective passes in Argentina. Godinho *et al.* (1991) captured in a fish pass 34 of the 41 species present in the region of the Salto do Morais dam. However, the fish pass seemed selective, there were few individuals of each species and only 2% of them reached the upper section of the fish pass. They mentioned another fish pass at Emas Falls on a low dam which seems to be more efficient.

As noted by Clay (1995), Latin American experience seems to be following that of other parts of the world, with limited success, because of lack of knowledge of the species involved and lack of application of the criteria needed for good fish pass design.

6. CONCLUSIONS AND RECOMMENDATIONS

Fish passes have been developed mainly in North America and Europe for a very limited number of target species present in these countries, mainly salmonids and clupeids. These species are the only ones for which reliable, quantitative data exists on the effectiveness of passes. The data is gathered from sources such as control station monitoring (trapping or video surveillance), or some marking/recapture or telemetry methods.

We may consider that the design technique for such passes is relatively well developed for these species. By respecting a certain number of design criteria on the pass itself, its location, the position of its intakes and flow, it is possible to design relatively effective passes in terms of percentage of the population able to pass and migration delay.

For other species, and particularly potamodromous or catadromous species such as eels, we have much less data on pass effectiveness. While we know how to design passes for such species, i.e. passes whose hydraulic conditions appear suited to the swimming abilities and behaviour of these species, we only have at best counts which are exhaustive to a greater or lesser degree. It is often difficult to assess the real efficiency of such equipment in so far as we do not know the migration needs and the size of population likely to use the pass.

Re-establishing fish passage upstream is only one of the aspects of dam-induced problems: there is also damage caused when the downstream migration and indirect effects linked to changes in water flow rates, water quality, the increase in predation and more particularly the loss or deterioration of upstream habitat.



Photo 29: The 15 m high Kernansquillec dam was decommissioned and destroyed in 1996 to restore the ecological quality, particularly the salmon population, on the Leguer river (Britanny, France). (Photo Larinier)

An accumulation of these factors, especially for high dams or a series of dams, may compromise the balance, and even the survival, of migrating fish populations. This remark is in keeping with the trend in both North America and Europe to demolish dams of limited usefulness or those considered to have a major impact on the environment. Three dams have been destroyed in France on rivers whose migratory population was the subject of a restoration programme. In the USA, Elwha and Glines Canyon dams, and four dams on the lower Snake river have been proposed for removal to restore the native salmon fisheries.

In countries with advanced fish pass technology for a very limited number of species, we may consider the passes to be an effective means of mitigation for obstacles not drastically modifying either the habitat conditions (by their height or their number in the case of series of dams), or water flow and quality. On the other hand, no quantitative data is available on the effectiveness of passes for most other species, particularly potamodromous or catadromous species.

The situation is very different in other countries, in particular in South America, Asia and Oceania. There are many migratory species whose biology, periods and stages of migration are little - or even unknown. Fish passes must accommodate species of very different sizes, swimming ability and migratory behaviour, especially small catadromous species with limited swimming abilities.

Fish pass design has in the main been based on American or European experience with salmonids, and most often with less-than-optimal design criteria. Passes are generally unsuitable for the species concerned. They are often undersized and not particularly well-suited to the rivers concerned. The attraction aspect of the passes has rarely been considered. Not only is the position of the fish pass entrance open to discussion but the flow rate inside it is insufficient and not usually in keeping with the scale of the river in question.

To resume, for such countries (most of which are developing countries), the maintenance of fish passages has almost never been correctly considered if indeed it has been considered at all. The effectiveness of such passes has very rarely been assessed and in such conditions it is not surprising that the situation may be considered catastrophic.

As noted by Quiros (1989) when discussing passes in South America, “the fact that almost nothing is known of the swimming ability and migration behavior of the native species in developing countries, coupled with the lack of available data on their behaviour means that it is impossible to establish broad guidelines regarding the most suitable fish pass designs.”

The priority is to acquire a better knowledge of fish communities, their biology and their migratory behaviour. This knowledge should enable us to better define the objectives of a fish pass in a given river and to design more suitable devices.

Suitable technologies should therefore be developed for contexts other than North America or Europe. Countries such as Japan and Australia have become aware of the specific nature of their problems and have undertaken to develop a technology suitable for their own rivers and their own species: two symposia were held in Japan in 1990 and 1995, and two workshops in Australia in 1992 and 1997, which enabled an overview to be drawn up and priorities to be outlined, i.e. “well resourced and directed research to determine migratory requirements, design programmes involving the appropriate mix of biologists and engineers, commitment to monitor all new or modified fishways, holistic approach identifying fish passage within a whole river rather than past individual barriers”. The results obtained already appear encouraging.

The fact that we do not know the migratory species, let alone their swimming capacities and migratory behaviour, is not an excuse to do nothing. Unfortunately, however, this is the option all-too-often adopted, such as the recent case of the Petit Sault dam on the Sinnamary river in French Guiana.

In the absence of good knowledge on the species, the fish passes must be designed to be as versatile as possible and open to modifications. Some fish passes are more suitable than others when targeting a variety of migratory species, such as vertical slot passes with successive pools, the drop between pools and energy dissipated in each pool being able to be adapted depending on fish size. Mechanical lifts (for the largest species) are to be avoided, as are Denil fish passes, which tend to be very selective. Furthermore, devices to monitor fish passage must be installed. This monitoring process will enable the fish pass to be assessed and the feedback thus obtained may be useful for other fish pass projects in the same regional context.

For high dams, when there are numerous species of poorly-known variable swimming abilities, migratory behaviour and population size, it is best to initially concentrate mitigation efforts on the lower part of the fish pass, i.e. to construct and optimize the fish collection system including the entrance, the complementary attraction flow and a holding pool which can be used to capture fish to subsequently transport them upstream, at least in an initial stage. This was the policy adopted by France in the 1980s for the first large passes for shad, until the technique had been fully mastered (Travade *et al.*, 1992).

Fish pass design involves a multidisciplinary approach. Engineers, biologists and managers must work closely together. Fish passage facilities must be systematically evaluated. It should be remembered that the fish pass technique is empirical in the original meaning of the term, i.e. based on feedback from experience. If you look at the history of fish pass techniques, it is clear that the most significant progress has been made in countries which systematically assessed the effectiveness of the passes and in which there was a duty to provide results. It is the increase in monitoring and the awareness of the need for checks which is at the origin of progress in fish pass technique in countries such as the USA, more recently France and Germany, and more recently again, Australia and Japan.

However, one must never lose sight of the limits to the effectiveness of fish passes. In addition to problems relating to fish passage, there are indirect effects of dams which may prove of major significance such as changes in flow, water quality, the increase in predation and drastic changes to the habitat up- or downstream. Complementary mitigation measures on flow management at certain times of the year, for example, could prove indispensable to the long-term maintenance of a good balance in migratory fish populations. The protection of migratory species for a given dam must be studied in a much wider context than the strict respect of fish passage alone.

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A REVIEW OF GUIDANCE AND CRITERIA FOR MANAGING RESERVOIRS AND ASSOCIATED RIVERINE ENVIRONMENTS TO BENEFIT FISH AND FISHERIES

by

Leandro E. Miranda
Mississippi Cooperative Fish and Wildlife Research Unit
Post Office Box 9691
Mississippi State, Mississippi, USA

EXECUTIVE SUMMARY

Few river systems have escaped impoundment. There are about 60 000 reservoirs worldwide with a volume larger than $10 \times 10^6 \text{m}^3$, representing a total volume exceeding $6\,500 \text{ km}^3$ and a surface of about $400\,000 \text{ km}^2$. Over 2 800 of these reservoirs have a volume larger than $100 \times 10^6 \text{m}^3$ and account for about 95% of the $6\,500 \text{ km}^3$ combined reservoir volume. Construction of dams has been driven by economic needs, while ecological consequences have received less consideration. Construction of reservoirs is slowing down in industrialized countries, but elsewhere construction continues at a rapid pace.

Reservoirs provide significant contributions to global fisheries. The main challenges to maintaining and enhancing reservoir fisheries and associated social and economic benefits are fish habitat and environmental degradation, inadequate fish assemblages, inefficient harvesting systems, stakeholder conflicts, and insufficient institutional and political recognition. This review examines existing measures, guidelines, and criteria available to manage reservoirs and their releases for the benefit of fish and fisheries in the river basin. The review considers measures for managing the environment, fish, and associated fisheries within the reservoir, as well as upstream and downstream. Issues associated with estuaries are also considered, but briefly. Once technical criteria and guidance relevant to managing the environment, fish assemblages and fisheries are addressed, the focus turns to improving management. Attention is given to administrative and procedural matters germane to the management process.

An important barrier to reservoir fisheries development and management is that fishery administrators find it difficult to defend the interests of their sector. Decisions over developments affecting fisheries and aquatic environments are often made with minimum or no consideration of these sectors, mainly for lack of reliable economic valuation and lack of political clout by the users. Given this lack of political power, the interests and needs of fishers and fisheries managers are often not properly represented within existing political frameworks, and thus neglected or ignored. Fishery administrators and stakeholders should seek every opportunity to communicate their needs, demonstrate the value of fisheries and the aquatic natural resource integrated by fish, and participate in the political process.

Management of impounded river basins in many developing countries follows models developed in North America or Europe. Strategies are often imposed by foreign experts or copied, considering neither climatic, faunal, socio-economic conditions, nor political realities. Despite the apparent commonality in environmental issues, management policy must be country-specific, and take local conditions into account; blind application of imported principles leads to policy failures. Although experience in other regions should not be ignored and should serve as the base for management plans, evaluation of strategies and revision to fit local realities are critical to successful adaptation and implementation.

A holistic approach to the management of fresh water as a finite and vulnerable resource must be taken, one that integrates economic, social, and environmental needs. Water allocation plans for river basins are essential to ensure that available water is adequately apportioned to meet this goal. The multi-sectoral nature of water resources development in the context of socio-economic development must be recognized, as well as the multi-interest use of water resources for water supply and sanitation, agriculture, industry, urban development, hydropower generation, inland fisheries, transportation, recreation, floodplain management and other activities. To this end, effective water management plans, coordination, and implementation mechanisms must be in place in all river basins.

Resource agencies can increase their effectiveness in developing reservoir mitigation by fully participating in the development process. However, to effectively recommend mitigation procedures, agencies need to incorporate technical expertise in fields other than traditional fish ecology and management, coordinate among other agencies, be willing to make recommendations based on incomplete information, have procedural expertise, and develop effective policies. Clear and effective policies for reservoir development can enhance an agency's influence in developing mitigation. The more thoroughly an agency can back-up mitigation recommendations with established regulations, policies, and specific scientific objectives, the more influence the recommendation will have. Broad policy and goals must be transformed into clearly defined targets and objectives.

Licensing and relicensing of dams may be used to ensure that reservoir construction and operation weights environmental concerns. Then, when deciding whether to issue or reissue a license, conservation, protection of fish and wildlife, fisheries, recreational opportunities, and preservation of general environmental quality benefits can receive equal consideration to energy or other economic benefits provided by impoundment. A relicensing process would provide an opportunity to modify old dams, and address problems created decades before environmental issues moved to the forefront. Relicensing would also provide an important medium by which the evolving public interest about river conservation can be addressed.

Sound management of impounded rivers depends on an ability to understand the effects of natural and human-induced change, which make management of impounded river basins extremely complex. Properly designed monitoring programmes that include repeated observations over time can separate natural effects from human ones, and distinguish effective management practices from less effective or harmful ones. Monitoring programmes are needed to support a comprehensive, scientifically-based evaluation of the present and future condition of the environment and its ability to sustain present and future populations.

Our understanding of impounded rivers and ability to predict how they will respond to management actions is limited. Together with changing social and economic values, these knowledge gaps lead to uncertainty over how best to manage impounded rivers. Despite these uncertainties, managers must make decisions and implement plans. Adaptive management is a way for managers to proceed responsibly in the face of such uncertainty. It provides a sound alternative to either charging ahead blindly or being paralysed by indecision, both of which can foreclose management options, and have social, economic and ecological impacts.

1. INTRODUCTION

Impounded rivers are relatively new aquatic ecosystems in the global landscape. They represent an important economic and environmental resource that provide benefits such as flood-control, hydropower generation, navigation, water supply, commercial and recreational fishing, and various other recreational values, particularly in developed countries. The ecological impacts of impounding a river have been dramatic and extensive. Construction of dams has been driven by economic needs, while ecological consequences have received less consideration. Construction of reservoirs in industrialized countries has slowed down after a peak near the middle of last century, because nearly all suitable sites have been impounded and ecological concerns have become more prevalent. In other parts of the globe, construction continues at a rapid pace (Avakyan and Iakovleva, 1998). Consequently, criteria to develop new reservoirs and understand their impact remain a need in some parts of the world, whereas demand for criteria to manage existing reservoirs to maximize their benefits and minimize or mitigate their ecological impacts continue to increase.

The geographic distribution of reservoirs reflects a complex interaction between topography, climate, and the economic need to control water movement through river basins. Water management goals tempered by climate have guided reservoir design, whereas economics tempered by topography have dictated their construction and operation. Some large river systems have been transformed into cascades of reservoirs by stacking them in chains. Examples include the Paraná in South America; Arkansas, Columbia, Missouri, and Tennessee in North America; Volga and Dnieper in Europe; Angara in Asia; Zambezi in Africa; and a many other large and small rivers. There are about 60 000 reservoirs with a volume larger than $10 \times 10^6 \text{ m}^3$, representing a total volume exceeding $6\,500 \text{ km}^3$ and a surface of about $400\,000 \text{ km}^2$ (Avakyan and Iakovleva, 1998). Over 2 800 of these reservoirs have a volume larger than $100 \times 10^6 \text{ m}^3$ and account for about 95% of the $6\,500 \text{ km}^3$ combined reservoir volume. Of these larger reservoirs, for which records are more reliable, 915 ($1\,690 \text{ km}^3$) occur in North America, 265 (971 km^3) in Central and South America, 576 (645 km^3) in Europe, 815 ($1\,980 \text{ km}^3$) in Asia, 176 ($1\,000 \text{ km}^3$) in Africa, and 89 (95 km^3) in Australia and New Zealand (Avakyan and Iakovleva, 1998). Few river systems have escaped impoundment.

Reservoirs provide significant contributions to global fisheries (Moreau and DeSilva, 1991; Petrere, 1996; Fernando *et al.*, 1998; Miranda, 1999). In North America and Europe, and more recently Australia, recreational fisheries are economically important, and the trend is for increased importance elsewhere. For instance in the USA, reservoirs attracted about 21 million recreational anglers in 1990, and supported over half of all freshwater fishing (USFWS, 1993). Commercial fisheries are most important in Asia, but are also important in Africa and South America. In some parts of the world, reservoir commercial fisheries are essential for subsistence and often represent an irreplaceable source of high-quality and low-cost animal protein crucial to the balance of human diets. Fish harvested from reservoirs are generally marketed regionally, and contribute to the livelihood of impoverished people and local economies. The main challenges to maintaining and enhancing reservoir fisheries and associated social and economic benefits are fish habitat and environmental degradation, inadequate fish assemblages, inefficient harvesting systems, stakeholder conflicts, and insufficient institutional and political recognition.

The purpose of this review is to examine existing measures, guidelines, and criteria available to manage reservoirs and their releases for the benefit of fish and fisheries in the river basin. Section 2 examines measures for managing the reservoir environment, as well as those upstream and downstream that influence the reservoir, or are influenced by the reservoir. Section 3 considers measures for managing fish stocks and fisheries in the reservoir and associated riverine environments. Section 4 identifies selected avenues for improving guidance, criteria, and the processes of managing impounded rivers.

2. GUIDANCE AND CRITERIA FOR MANAGING FISH ENVIRONMENTS

2.1 The Watershed

Point and non-point source pollutants imported from the watershed affect environmental quality in reservoirs. Point source pollutants consist mainly of contaminants and particulate and dissolved organic matter that can be traced to a localized source (e.g. a sewage outlet, industrial discharge). Non-point pollutants originate from diffuse sites (e.g. farm lands) throughout the watershed and include silt and clay, inorganic nutrients, particulate and dissolved organic matter, and contaminants (e.g. pesticides). The reservoir sediments represent a composite of materials originating from point and non-point sources. Although point sources can often be regulated, non-point sources in large watersheds are more difficult to control. Nevertheless, interagency efforts that result in watershed and reservoir improvements have been documented (Born *et al.*, 1973). Sediments, excessive nutrients, organic matter, and contaminants may be kept out of reservoirs through proper agricultural and waste management practices.

2.1.1 Sediments

Reservoirs effectively trap suspended solids, sedimentation increases turbidity to limit primary production, and decreases depth and thereby storage capacity, all of which affect various physical and chemical processes that eventually influence the biotic community. Sediments originate from erosion processes within the drainage area, the river channel and the reservoir shore, and are normally the major non-point source of pollution. Sedimentation is aggravated in basins characterized by prolonged droughts followed by seasons with heavy rains such as in Brazil (Gomes and Miranda, in press, a), or by monsoon seasons such as in India (Sugunan, 1995). Practices to reduce loads of sediments and nutrients entering rivers and reservoirs include conservation tillage, terracing, crop rotation, vegetative cover, crop residue, nutrient management, streamside management zones and use of structural devices such as retention basins, sediment dikes, and erosion control weirs (Johengen *et al.*, 1989).

2.1.2 Nutrients

Phosphorus inputs and regeneration from sediments are the major factors driving autotrophic production. Forsberg & Ryding (1980) considered lakes with total phosphorus concentrations $<15\mu\text{g L}^{-1}$ as oligotrophic, 15-25 as mesotrophic, 26-100 as eutrophic, and $>100\mu\text{g L}^{-1}$ as hypereutrophic. Phosphorus inputs often come from agricultural sources and municipal effluents. Excessive inputs result in rapid eutrophication. The consequences of eutrophication are algal blooms, which cause decreased water clarity, wide dissolved oxygen fluctuations, and dense littoral beds of aquatic vegetation. Through effects on water physical and chemical characteristics, dense algae blooms make reservoir environments unsuitable for many fish, reducing diversity of fish assemblages and fisheries. Management strategies to curtail eutrophication include dilution and flushing, aeration of hypolimnion and circulation to encourage utilisation of nutrients, precipitation and inactivation, sediment removal, water level drawdown, hypolimnetic discharges, and harvesting of biota (e.g. macrophytes and fish) (Cooke *et al.*, 1993).

2.1.3 Organic Matter

Inputs of organic matter can be beneficial or harmful, depending on the natural fertility of the basin and the nature of the system. Particulate organic matter is the basis of food chains in large, turbid reservoirs where autotrophic production is limited by turbidity and low retention time. However, smaller reservoirs that tend to be higher in watersheds are often less turbid, have higher retention, and are more autotrophic, and can thus be overwhelmed by the oxygen removal due to decomposition of large organic inputs.

2.1.4 Contaminants

Contaminants may include metals, pesticides, oils, and other pollutants in industrial, agricultural, and urban wastes. Elevated levels of these substances can reduce fish survival, reproduction, and growth and may bioaccumulate in fish tissue often rendering them unsuitable for human consumption (Cairns *et al.*, 1984). Possible corrective actions include eliminating the point sources and managing the watershed (Baker *et al.*, 1993). Aeration of the hypolimnion can oxidize some contaminants and encourage precipitation. Changes in water level may need to be adjusted if the exposure and suspension of contaminated sediments tend to increase the solubility and mobilisation of contaminants. Removal of contaminants is sometimes not possible and no action may often be the only approach, allowing natural processes such as sedimentation to gradually remove the substances. Such an approach requires considerable monitoring and possible closure of some fisheries.

2.2 The River Upstream

Sedimentation problems on regulated rivers are considerably different from natural rivers. Problems include sedimentation in reservoirs, channel effects downstream of dams, and in-stream flow requirements for maintenance of channels and fisheries. Reservoirs can profoundly affect the geomorphology of streams that have a large natural sediment load, as the reservoir traps sediments and releases clear water. The resulting downstream geomorphic effects of clear water releases from dams typically include channel instability (as the channel and banks are eroded to satisfy the sediment carrying capacity of the waters), channel bed armoring, and alteration of habitat (Collier *et al.*, 1996).

Instability of tributary streams can produce negative effects on habitat for riverine fish and those that occupy the reservoir but need riverine habitat to complete their life cycle. The extent and magnitude of stream bank erosion is greatly increased by activities that remove riparian vegetation, increase water flows, increase sediment movement, or otherwise cause channel down-cutting (Meehan, 1991). Large vessel traffic and the resulting wakes also can create bank scour. Moreover, in-stream mining can cause multiple effects on fish habitat.

Attempts to deal with bank erosion often involve the use of hard materials (Orth & White, 1993). In smaller streams, particularly those that seasonally become dry or nearly dry, bulldozing of streambed gravel against the banks has been a common practice to retard erosion. In rivers, the placement of rip-rap rock, broken concrete, and mixtures of materials (ie rocks, soil, branches) along the banks has been a common practice. More recently, soil and vegetation bioengineering such as grading or terracing a problem stream bank or eroding area, and using interwoven native vegetation mats installed alone or in combination with structural measures, are being used to stabilize stream banks. Once these features are protected, they can also serve as a filter for surface water runoff from upland areas, and as a sink for nutrients, contaminants, or sediments.

However, erosion of banks is a natural process of rivers. River channels move freely from side-to-side across floodplains by eroding the banks on one side while depositing sediment on the other. This dynamic characteristic results in constant creation of new fish habitat and many species depend upon a constantly changing river. Impoundments have changed how the river erodes its banks, and in many cases the erosion is occurring through down-cutting, but new lateral habitat is not being created.

In reservoirs with long stretches of riverine environment upstream, large lateral tributaries, or both, native potamodromous fish comprise a large proportion of the fisheries (Agostinho *et al.*, 1995). These reservoirs often have low retention times and are generally not conducive to development of lacustrine faunas (Gomes & Miranda, in press, a). In such reservoirs, upstream riverine habitats should be a conservation priority. Examples include Itaipu Reservoir, where a 230 km stretch of the free-flowing Paraná River connected to an extensive floodplain provides important spawning and rearing habitats for

many species in the fishery. In 1998, at the urging of conservationists and fishers, this section of the river was set aside as a national park by the Brazilian government, to prevent further impoundment, degradation, and enhance fisheries in Itaipu Reservoir (Agostinho *et al.*, in press).

2.3 The Reservoir

2.3.1 Siting

Characteristics of a river along a continuum from its upper to lower reaches often change continuously and dramatically. Characteristics that may be greatly modified by a dam such as temperature, nutrient levels, plankton production, and biodiversity may be affected differently by damming the upper, middle, or lower reaches of a river system (Ward & Stanford, 1983). A headwater dam can greatly depress the ratio of coarse particulate to fine particulate organic matter below the impoundment because in-stream transport of detritus is blocked, whereas impounding the lower reaches of the river may have little effect on the composition of detritus. Correspondingly, functional feeding groups of invertebrates and fish can reflect these changes in detritus, whereas a dam on the lower reaches may not greatly alter the trophic relations of the receiving stream.

Stream characteristics are sometimes most diverse in the middle reaches. For example, flow discharge patterns in the upper and lower reaches of rivers tend to be less variable. In the upper reaches, constancy of discharges may be influenced by feeding springs and by the moderation of precipitation by terrestrial watershed processes; in lower reaches, excessive variation may be prevented by the collection of waters from many tributaries (Hynes, 1970). The middle reaches are generally most influenced by local meteorological events that may vary widely among geographical regions within the river basin, and hence these reaches tend to exhibit the most variable and unpredictable flows. Reservoirs moderate flow fluctuations in the middle reaches by storing water during periods of major runoff and releasing water during period of low flow (Ward & Stanford, 1995). Thus, reservoirs can have more impact on flow regimes of middle reaches as compared to upper and lower reaches.

These patterns of environmental heterogeneity along a stream continuum influence biodiversity. The high biodiversity in the middle reaches of a river system may result from spatial and temporal heterogeneity (ie unpredictability of flow, temperature, and other characteristics); increased predictability due to impoundment may result in reduced biodiversity. Impoundments in the upper reaches, however, are likely to influence biodiversity less by altering environmental heterogeneity and more by disrupting transport and processing of allochthonous materials. Impoundments in the lower reaches can limit migratory fish. In general, effects of impoundments along a river system continuum are likely to be less severe when dams are placed in the upper reaches than when placed in middle or lower reaches; nevertheless, severity of effects is related to a multiplicity of other factors that may easily override the effect of location in the river continuum.

Moreover, reservoirs positioned in the upper reaches have higher water retention times, and thereby develop fish assemblages more characteristic of lake environments. In the Paraná basin, large drainage areas and low water retention times of reservoirs in the lower reaches, exacerbated by high rainfall during spawning and rearing periods, limited the emergence of fit reservoir species from within the existing pool of riverine species (Gomes and Miranda, in press, b). The resulting assemblages have characteristics that are neither riverine nor lacustrine, and are maladapted to support fisheries. Introduction of lacustrine species (discussed below) are destined to failure because environmental characteristics are not lacustrine, except in reservoirs positioned high in the watershed where increased retention time allows development of lacustrine, autotrophic conditions. For example, Billings Reservoir, high in the Upper Paraná basin, exhibited greater hydraulic retention time and more autotrophic production, characteristics of lacustrine environments where assemblages rely more on grazing food chains. Coincidentally, this reservoir supported the greatest fisheries yield in the basin.

Various considerations are juggled in siting a reservoir. Engineering economics dictate that reservoirs be constructed with a high ratio of reservoir volume to dam volume, and thus reservoirs are preferably built in narrow, steeply sloped reaches that have broad valleys branching upstream. Other site requirements include topographic relief that provides a favorable reservoir surface area to volume ratio (ie sufficient storage volume without excessive shallow areas); and an alignment that does not allow a strong influence of prevailing winds (to avoid erosion and excessive turbidity). From an environmental perspective, biodiversity of the riverine fauna is a major philosophical issue. Impoundment of a river system will generally negatively impact biodiversity; thus, rivers with unique faunas may need to be spared. Effect of human populations is another major concern. Siting a reservoir near a populated area may enhance quality of life through economic and technological advances, while providing various recreational opportunities. Conversely, such siting may lead to relocations or severe cultural impacts. Prognosis for eutrophication should be considered; rapid eutrophication leads to decreased return on investments and short-lived reservoirs.

Some physical features of the reservoir basin can be avoided or modified during construction to substantially improve fish habitat and fisheries. There are various specific factors relevant to fisheries management that should be considered during site selection and reservoir design. The watershed should be well vegetated to prevent excessive erosion that leads to sedimentation, and free of pesticides and other pollutants. Runoff from agriculture, livestock operations, and industrial sites should be treated or diverted. Limited shore development and no septic discharges should be allowed. Watershed size influences water level fluctuation and retention time. The optimal watershed size depends on lake volume, rainfall, topography and land uses. Retention times less than about four weeks limit autotrophic production and retention times larger than about a year are associated with strong stratification (Søballe and Kimmel, 1987; Søballe *et al.*, 1992; Straškraba, 1999). The level of vegetation removal from the reservoir's basin during construction varies depending of the main purpose of the reservoir. It is often desirable to leave blocks of timber and brush in embayments and shallow arms to enhance fish habitat. Although most of the evidence comes from the west, DeSilva (1988) corroborated such practice in Asia but called for more research. Often fish cover and spawning habitat can be improved during reservoir construction. Extremely deep reservoirs are generally unproductive, whereas extremely shallow reservoirs may remain turbid or support excessive growth of aquatic macrophytes. Additionally, the minimum flow requirements to support aquatic organisms in downstream areas should be addressed. Determination of minimum flows is often problematic. Minimum flow requirements are typically determined to protect or enhance one or a few harvestable species of fish; other fish, aquatic organisms, and riparian wildlife are assumed to be protected by these flows as well.

2.3.2 Erosion and Sedimentation

Wetting through water level fluctuations saturate previously unsaturated material, potentially resulting in massive slides when the water level is drawn down (USACOE, 1987). This material accumulates at the base of the slope, and often forms an underwater bench, leaving steep unstable slopes above the water line. Reservoir banks are also subjected to attack by both wind itself and waves generated by wind or power boats, which tend to remove this material and undercut the banks. Sediment deposits originating from erosion within or outside the reservoir are of concern, as they impact not only the reservoir storage capacity but also many biological processes. Sediments deposit not only in the lower reservoir zone frequently reserved as a sediment pool, but often throughout the littoral causing shallowing and loss of productive substrates. The suspended solids and sediments derived from erosion and deposition damage fish habitat and produce adverse impacts like those described for non-point sources of sediments. Barren shores and mudflats are poor food producers, unsuitable habitat for nest builders, and poor nursery habitat for fish (Meals and Miranda, 1991).

Some water level management practices can minimize erosion and sediment deposition. Minimisation of the rate with which water level is drawn down helps reduce slides. Keeping reservoir level as low as possible during known periods of high sediment inflow encourages sediments to deposit in the lower

zones of the pool. Periodically raising water levels high enough to inundate existing sediment deposits, reduces the establishment of permanent vegetation and subsequent increased sediment trapping in backwater reaches (USACOE, 1987).

Landscaping and waterscaping options to reduce shore erosion and sediment deposition include steep sloping shores with terracing above the water line; construction of retaining walls, rip-rapping with rocks, and installation of gabions; construction of breakwater structures to reduce the energy of waves; and encouraging growth of aquatic or terrestrial vegetation nearshore in reservoirs not subject to large water level changes. The most sensitive sites are often those exposed to long fetch. Buffer strips of natural vegetation along the shore also help to stabilize shorelines, reduce sediment inputs, and provide shading that produces cooler water temperatures. Protection against shore erosion can be very costly, and often must be limited to specific areas of concern (Summerfelt, 1993).

The effects of shore erosion on the aesthetics of the reservoir are closely related to its use for recreational purposes, and should be considered in the management of water level fluctuations. Often, aesthetics may be improved simply by minimising the duration of exposure of unsightly shorelines resulting from erosion. However, in some reservoirs it may be virtually impossible to compensate fully for such effects and still maintain the integrity of the functions for which the reservoir was constructed.

2.3.3 Aquatic Vegetation

Fish and fisheries generally benefit from availability of moderate levels of plant cover; thus, absence of aquatic vegetation can be as harmful as excess (Dibble *et al.*, 1996). Aquatic macrophytes also help stabilize sediments and shoreline, reducing problems associated with erosion and turbidity. The goal of aquatic plant management is to identify and provide an appropriate level of aquatic vegetation taking into account the effect of plants on the existing fish assemblage, reservoir physical characteristics, and uses of the reservoir.

Several management measures are available for reducing excess aquatic plants (Baker *et al.*, 1993; Summerfelt, 1993). The control technique to be used is dependent upon the species of aquatic plant causing the problem, magnitude of infestation, distribution within the reservoir, and characteristics of the reservoir, and full consideration should be given to the impact of the control measures on fish and fish food organisms associated with aquatic plants. The degree of control required to bring the problem to an acceptable level must also be a consideration. Aquatic plants that cause problems in reservoirs are generally of the floating and submersed types. Biological, chemical, and mechanical methods, individually or in combination, may be used to control aquatic plants. Biological control employs organisms that feed on the target organism or affect it in some other way to reduce its density or growth. Biological control agents potentially available for use in aquatic plant control are insects, plant pathogens, and herbivorous fish. The application of safe and effective chemical agents is a proven method for aquatic plant control. Approved chemical agents for aquatic use may be liquids that can be sprayed onto floating plants or inserted under the water for controlling submersed plants, or they may be solids that can be applied by spreaders. Chemical methods are generally readily available and are relatively inexpensive when compared to other methods, unless used in large areas. Mechanical devices for controlling aquatic plants vary from deflecting booms and screens or clipping bars mounted on boats, to more sophisticated systems whereby the plants are cut and removed from the water to disposal areas. Although most mechanical methods are generally rather costly, they are sometimes desired over other methods because no organisms or chemicals are added to the environment. In reservoirs where water level can be lowered, reductions of some submersed species may be achieved through exposure to drying or freezing; however, some species are not affected or even encouraged by such drawdowns. In general, biomanipulation through introduction of herbivorous fish is the less costly control method where infestations are large. Nevertheless, introductions may be environmentally costly if fish leave the reservoir and affect desired aquatic vegetation in streams, associated wetlands, or even estuaries (Summerfelt, 1993).

Establishment of aquatic plants has proven difficult in those reservoirs that do not already have them, and some reservoirs may never develop an aquatic plant community. The lack of aquatic vegetation in many reservoirs may be attributed to the absence of propagules in the impounded basin, but may also be due to inhospitable environments for establishing seedlings (e.g. turbidity, unnaturally fluctuating water levels, inadequate substrates, excessive density of herbivores). Through time, seed banks may develop and reservoirs develop aquatic flora. Through planting, management of water levels and turbidity, and exclusion of predators, aquatic plants can be established and the system driven towards a vegetated, clear state (Smart *et al.*, 1996).

2.3.4 Destratification

Low temperature and concentrations of oxygen tend to occur in the hypolimnion when reservoirs stratify. Vertical stratification occurs mainly through the interaction of wind and temperature and creates density gradients that affect water quality. Intensity of the gradient varies latitudinally, and is affected by physical characteristics such as reservoir depth, water retention time, and water level fluctuation. Oxygen stratification is undesirable because anoxic conditions in the hypolimnion limit habitat availability and can impact water quality throughout the reservoir and downstream.

Methods to destratify or prevent stratification include hypolimnetic discharges, air bubbling/injection to generate water movement, and mechanical pumping between the hypolimnion and epilimnion to either generate water movement, or to aerate hypolimnetic water by passing through baffle systems (Ruane *et al.*, 1986). A bubble column produced with compressed air will create upwelling in a reservoir that, in combination with wind energy, can be used to prevent stratification or to destratify (Pastorok *et al.*, 1982). Mechanical pumping can also be used to avoid oxygen stratification without disrupting temperature stratification, by lifting hypolimnetic water to the surface where gases such as methane, hydrogen sulfide, and carbon dioxide are dispersed, and then water is returned to the hypolimnion without substantial increases in temperature (Wirth, 1981), which may allow maintaining both warmwater and coldwater fish communities and fisheries. Aeration of the hypolimnion through injection of oxygen has been reported to be more cost effective than through lift systems (Mauldin *et al.*, 1988). Potential benefits of artificial destratification include expanded habitat for invertebrates and fish, improved quality of water stored and released, retarded eutrophication, and avoidance of catastrophic turnovers.

2.3.5 Water Levels

The littorals of reservoirs are usually highly unstable when water levels fluctuate. Fluctuations may be daily, seasonal, or annual depending greatly on the reservoir purpose, and present many problems to fish habitat management. However, operation curves often have enough flexibility to allow development of management opportunities.

Water levels have a direct effect on benthos, periphyton, and aquatic macrophytes abundance, but only indirect effects on phytoplankton and zooplankton (Ploskey, 1986). Increases in water level that inundate lush vegetation temporarily increase supply of food and cover, whereas extensive drawdowns concentrate fish and can increase foraging efficiency of predators. Reproduction of littoral spawners may be encouraged by flooding of shores (Miranda *et al.*, 1984), but can be adversely affected if levels increase or decrease rapidly during the reproductive period, particularly nest builders or substrate spawners. Because year-class strength of fish varies annually depending on environmental conditions, optimisation of water levels for fish spawning may not be essential or productive every year.

Because substrates exposed by drawdown are subject to erosion, establishment of herbaceous vegetation after drawdown is important for erosion control and aesthetics. To be effective, drawdowns must occur during the growing season for successive seeding of herbaceous terrestrial vegetation and should allow for substantial grow before winter. Such drawdown also provides the opportunity to improve submerged

structures that enhance habitat diversity for littoral species. Managers in temperate North America generally drawdown reservoirs in late summer or fall to allow establishment of terrestrial vegetation naturally or by seeding, flood terrestrial vegetation in spring when most species spawn, maintain constant water level during spawning season, and maintain water level as high as possible until the following drawdown (Willis, 1986). In general, water level manipulations are most effective when they are extensive, last several months, occur during the growing season, and flood or drain productive areas. On very large reservoirs where drawdown even of a small magnitude would result in huge water losses, this method of optimising littoral conditions for fish may not be practical.

In some African reservoirs water level must be managed to maintain intermediate levels of submersed aquatic vegetation. The aquatic vegetation provides food and shelter for key species in the fisheries. Bernacsek (1984) proposed to fluctuate water level 2.5 to 4 m annually to disallow excessive proliferation without eliminating the vegetation, which is possible with greater fluctuations. Drawdown rates not to exceed 0.6 m per month were needed to allow adjustment of littoral communities to the fluctuating water levels. In reservoirs of the Tennessee River, USA, the Tennessee Valley Authority stabilises water level within ± 0.6 m for at least two weeks once water temperature reaches levels at which most littoral fish species begin spawning.

Where a system of reservoirs exists, operational flexibility to provide appropriate seasonal water level increases further down the chain. With coordinated scheduling, flooding and drawdowns may be provided to a reservoir at least every 2-4 years. Power and water demands may be met by releases from other reservoirs in the chain. Fishery managers should be familiar with rule curves (man-made hydrographs), operational needs, and fishery needs to be in a position to suggest modifications to water managers.

2.3.6 Fish Habitat

Fish production in some reservoirs may be limited by the availability of suitable spawning sites or poor quality of available sites (Summerfelt, 1993). Siltation is a major cause of degraded spawning habitat, but silt removal is impractical in most situations. Instead, raising water level during the spawning season, annually or otherwise, often creates suitable spawning substrate for nest-building species. In some instances it may be possible to construct sites where important species may spawn (Karpova *et al.*, 1996). Gravel beds and reefs constructed of large rocks often attract reservoir species. Some species spawn in coves, lagoons, flooded wetlands, or other heavily vegetated flooded areas in river floodplains. These areas may also serve as nursery areas. These areas are often present in the headwaters of the reservoir and should be protected and managed; alternatively, raising water level during spawning and rearing period may artificially produce similar environments.

Some reservoirs may lack sufficient structural features to provide shelter. Without adequate shelter, survival of young fish of many species is often low, preventing adequate fishery yields. Structural features provide safety from predators, substrate for food organisms, and even spawning habitat. Also, some predators tend to concentrate around structural features searching for prey, and such concentration may enhance fishing success. Common types of physical structures include drowned or fallen trees, brush piles, rock reefs, and sharp changes in the bottom topography. Reviews on addition of physical structures to provide cover and spawning areas are provided by Ploskey (1985) and Brown (1986).

2.3.7 Reservoir Aging

Aging of reservoirs is intricately linked to inputs from the watershed, and siltation is perhaps the most dominant aging process. Siltation reduces depth, affecting storage capacity of the reservoir and most importantly the characteristics of littoral habitats, particularly in embayments. These long-term depth reductions lead to slow changes in bottom firmness, as well as average, minima, and maxima values of temperature, oxygen, and other vital water quality conditions. Silt is likely to be rich in nutrients and organic matter also imported from the drainage area, which become available for primary production.

Ultimately, this production promotes further release of organics and nutrients as they decay, and further eutrophication of the sediments. Reductions in oxygen prompted by decreased depth are exacerbated by increased sediment oxygen demands. In arid, agricultural regions of the dry zone of Asia, aging is also associated with salinisation prompted by excessive evaporation and leaching of minerals in soils (Petr and Mitrofanov, 1998).

As the reservoir ages and siltation progresses, nutrient dynamics of the system begin to change. With increased nourishment, phytoplankton communities shift from a domination by green algae to blue-green algae. Although dominance may also shift seasonally, in highly eutrophic reservoirs blue-green algae tend to dominate for an increasingly larger portion of the year (Wetzel, 1983). Zooplankton composition is affected by phytoplankton availability. Macrofiltrators (usually large-bodied zooplankton) are more abundant in younger, oligotrophic reservoirs, sometimes giving way to low-efficiency, small-bodied, algal and bacterial feeders as reservoir age and nutrients increase (Taylor and Carter, 1998). Additionally, in highly eutrophic aging reservoirs the food supply of zooplankton may actually decrease because of the dominance by blue-green algae, which are mostly inedible due to their large size (Porter, 1977). These interrelations between phytoplankton and zooplankton can have repercussions higher through the food web. As a result the fish community shifts to a less desirable assemblage of increased benthophagous and phytophagous species and reduced predator densities. Nevertheless, these changes are likely to occur over long terms.

Increased nutrient loads encourage growth of free-floating macrophytes, such as *Eichhornia* spp., whereas depth losses foster growth of rooted aquatic macrophytes and expand their distribution from shore (Cooke *et al.*, 1993), if water level fluctuations are not large. Extensive macrophyte development can exert enormous control over the aquatic ecosystem, beginning with the physical and chemical characteristics of water (e.g. temperature, light, oxygen). Once extensive covers of submersed aquatic macrophytes (e.g. *Hydrilla*, *Myriophyllum*) become established, they can aggravate eutrophic conditions of an aging reservoir through growth-death-decay cycles that allow release of nutrients trapped in sediments, under anaerobic or aerobic conditions.

Other major change induced by aging is the deterioration of various habitats, particularly in the littoral zone (Benson, 1982). Standing timber often left in the basin decompose and fall. Long-term bank erosion induced by wind damage of exposed shorelines turns diverse shoreline habitats into uniform, barren mudflats. In reservoirs with substantial water level fluctuations, this effect is not limited to the normal pool shore, but extends into areas above and below normal pool elevation, and can expand a substantial percentage of the littoral area depending on the slope of the reservoir basin. The original productivity of this ecotone is thereby lost with age, and its instability precludes colonisation by terrestrial or aquatic flora.

2.4 Fish Passage

Elimination or reduction of spawning grounds, or delayed access to the spawning areas have been the most significant effects of physical barriers. Dams can affect fish by blocking upstream and downstream passage. These movements are most important to anadromous and catadromous fish, which spend part of their life cycles in rivers and part in oceans or other large waterbodies, but also to potamodromous species which, during a certain phase of their life cycle, depend on longitudinal movements within the river system (FAO, 1998). For fish trying to move upstream, a dam can pose an impassable barrier unless passage is provided, and fish moving downstream are at high risk of being entrained in the turbine intake and injured or killed during downstream passage.

2.4.1 Upstream Passage

The blockage of upstream fish movements by dams may have serious impacts on species whose life history includes migrations for various purposes, e.g. spawning, feeding. Anadromous, catadromous, potamodromous, and some resident fish could all have spawning migrations constrained by such barriers.

Maintenance or enhancement of such species may require the construction of facilities to allow for upstream fish passage. Descriptions of the design and functioning of various types of upstream passage facilities have been provided by many authors (e.g. Orsborn, 1987; Larinier *et al.*, 1994; Clay, 1995; DVWK, 1996; Jungwirth *et al.*, 1998). Upstream passage facilities can broadly be divided into two general categories (FAO, 1998): largely natural structures (e.g. fish slopes or rock ramps and by-pass channels) and more technical ones (e.g. pool-type fish passes, Denil fish passes, vertical slot passes, fish lifts and fish locks). Trapping and hauling is yet another option for bringing fish upstream around an obstacle. Fish passes are widely used to allow fish to get over single obstacles such as dams and may also be used to collect fish for hauling to upstream releasing locations.

According to Orsborn (1987), the term “fishway” describes any flow passage that fish negotiate by swimming or leaping, e.g. an artificial structure such as a culvert, a series of low walls across a channel (weir-and-pool fishway), or merely a chute up which the fish swim. Additional definitions are given by Clay (1995); he points out that the terms “*fishway*” and “*fish ladder*” are used in North America, whereas “*fish pass*” is used in Europe. Fish passes can also be classified according to the behaviour of fish, i.e. some types of fish passes enable fish to swim upstream under their own effort whereas fish lifts and fish locks lift the fish over an obstruction.

The wide variety of fish pass designs has been reviewed periodically (Orsborn, 1987; Larinier *et al.*, 1994; Clay, 1995). An extensive review of fish passages in relation to dams is provided by Larinier (2001, this volume). As with the hauling of fish, substantial experience in design and operation of fish passes, dating back to early in the last century, has led to the development of standard design criteria (Clay, 1961). Modern fish passage philosophy includes at least five important general aspects as to the design and construction of efficient fish passes. First, speed and success of fish passage must be optimized to minimize delay, stress, and damage of fish. Second, the discharge through a fish pass has to be adapted to the needs of the target species and negotiated accordingly with the other potential or existing water resource users. The available volume of water should be used in an optimized way. Third, the fish pass should be optimized for the widest possible range of stream flows that can be expected at the time of migration of any of the target species. Fourth, funding for construction, operation, and maintenance should be allocated in such a way as to guaranty the best possible functioning of the fish pass. Lastly but not least, safe downstream migration has to be considered. Optimising the first element, i.e. effectiveness, is a challenge especially if the goal is to pass a variety of fish species that have different behaviours, sizes, and swimming abilities, but it is today technically feasible by selecting the most appropriate type of fish pass for a given situation. Unfortunately, the most successful and cost-effective fish passes are often those designed to allow passage of one or a few target species during a narrow time period, e.g. a run of anadromous fish that have a uniform size and predictable behaviour. Although some species are reluctant to pass through fish passes, in many cases species-specific structural modifications of the fish pass can encourage passage. The improved fish lift at Golfech on the Garonne River in France is a good example of how to pass a “difficult” species, i.e. Allis shad, *Alosa alosa* (Larinier *et al.*, 1994). There also exist numerous examples of non-target fish species using fish passes to surmount obstacles (Schwalme and Mackay, 1985; Slatick and Basham, 1985).

Costs must not be a criteria for not choosing the optimal solution; the “User-Pays Principle” (cf FAO, 1997) must be applied, i.e. users of the water and the basin should minimize any deleterious effects and contribute to the mitigation of any impacts of their activities and to rehabilitate the systems when the need for their activity has ceased. In other words, the users of the water resource impeding fish passage by putting an obstacle should bear the expenses of carrying out the measures to ensure free and unhindered passage, both upstream and downstream, through a well functioning fish pass and/or by-pass and pay for rehabilitation, e.g. decommissioning of a dam, at the end of an activity. Furthermore, the users have to prove the effectiveness of the fish pass facility through monitoring at their costs. Where a fish pass does not prove fully effective, improvement is needed. Ideally, a fish pass should be permanently open to passage; if this is not possible, the migration periods of the different species have to be taken into consideration to ensure that the facility is functional at critical times.

In fact, fish passage facilities have been installed in many rivers where migratory species are major components of the fish assemblage. These facilities may include fish passes, fish elevators, fish locks, powerhouse collection galleries, tailrace fish diversion screens, spillways or outlet works that provide water to attract fish into fish passage facilities, and juvenile by-pass facilities. In addition to these physical facilities, other activities to facilitate passage may include transporting fish by truck and barge, increasing streamflow through reservoirs during migration to facilitate downstream movement of juveniles, modifying spillways to reduce nitrogen supersaturation during times of spill, and adjusting or reducing spill to help mitigate nitrogen supersaturation.

Trapping and hauling is a labour-intensive mitigation measure that can be used when fish need to be transported long distances upstream or around a large number of obstacles. Upstream-moving fish may be collected at a single location (e.g. the farthest downstream dam) and transported by tank truck to upstream releasing locations. The techniques and factors important to the survival of transported fish are relatively well understood based on experience with hatchery fish. However, it is more challenging a method for moving wild fish past a dam because collection is more difficult under the given hydrological circumstances below a dam, and target fish may concentrate near the dam for only short periods of time.

Dependence upon technology to provide passage around dams has not always been successful. On some occasions where upstream fish passage facilities have been provided, migration delays and mortality of adults persist. Poorly designed fish passes can inhibit movement of adults upstream, causing migration delays, increased pre-spawning mortality, and reduced reproductive success of the fish that eventually reach their spawning grounds.

The characteristics of the attraction current, and thus especially the design of the entrance, are very important to attract and guide adults into passage facilities. To attract fish, appropriate flow and water temperature must be available in the channel area adjacent to and immediately downstream from the entrance to the passage facility. These attraction currents are crucial in leading the upstream migrant fish into the fish pass from the tailwater area or open-river. Uncontrolled water spills at weir shutters or sluice gates can mislead the fish with a risk of injury. Relatively large amounts of water can be required to create suitable flows (30-60 m³ s⁻¹ for salmonids), and these may be supplied by large capacity pumps, a hydroelectric unit whose draft tube discharges into the passage approach channels, or by direct diversion of water from the headwater to the approach channels through gravity supply systems.

The *modus operandi* of the turbine(s) could be a determining factor in fish finding the entrance into a fish pass. It is a well-known fact that optimal positioning of the entrance(s) of a fish pass relative to the turbine outlet is critical. Less, however, is known about the importance of sound turbine management on fish passage, e.g. the number of turbines operating at a given time, the position of operating/not operating turbines relative to the entrance (turbine next to entrance turned on or off, or running at reduced rate), the modulation of the turbines (degree of flow-through compared to maximal capacity). Further research and tests are needed to clearly determine the degree of influence of turbine management on fish pass effectiveness and efficiency. Until more is learned, it is recommended that a diversity of turbine operation cycles be provided during migration periods to benefit the greatest number and species of fish. The commanding and operation cycle of the turbines should therefore be adjusted to the needs of the migrating species. The turbine's rotation direction, and thus the orientation (spin) of the turbine outflow, relative to the entrance of the fish pass could also turn out to be an important factor. Tests of a prototype fish collection facility (a sort of collection gallery) with three entrances at one hydropower production site on River Lahn in Germany suggest that it was likely that the spin of the water coming out of the turbine determined the attractiveness of one entrance location compared to another (Adam and Schwevers, 1998). For new dam projects, the effect of the rotation direction of the turbine(s) on fish should be studied beforehand (maybe as part of the EIA).

2.4.2 Downstream Passage

Dams are also barriers to downstream passage of juveniles and adults that have spawned in upstream areas (e.g. salmonids and some potamodromous species) or that are on their downstream spawning migration (e.g. eels). The size, morphology, and retention time of the reservoir may limit downstream passage of juveniles through increased migration time caused by reduced currents, exposure to less favourable water quality and habitat conditions, and increased exposure to predation. At dams, injury and mortality of juveniles occurs because of passage through turbines and sluiceways. Impact with turbine blades, rough surfaces, or solid objects can cause death or injury. Changes in pressure within turbines or over spillways also can result in death or injury. Juveniles, frequently stunned and disoriented as they are expelled at the base of the dam, are particularly vulnerable to predation. Below hydroelectric facilities, nitrogen supersaturation may also negatively affect migrating fish by causing gas-bubble disease. Mortalities from gas-bubble disease increase in years of high flow and high spill. The severity and outcome of gas-bubble disease depends on the level of dissolved-gas supersaturation; duration of exposure to supersaturated water; water temperature (warmer water can hold less gas, and can therefore become supersaturated at lower pressures); health and condition of the fish; and swimming depth of fish (Marking, 1988). Eels are often injured or killed during turbine passage. Most frequently, adult salmonids end up either blocked at, or squeezed onto, the trash racks, or pass the dam in spill flows. Cumulative effects may occur where migrants encounter several dams in their downstream passage.

In view of the difficulties of passing downstream juveniles migrating past large dams, particularly those with hydroelectric facilities, a number of alternative methods have been tested in order to achieve the most satisfactory and economic solution. A variety of downstream fish passage and screening devices has been used to prevent fish from being drawn into turbine intakes (see also Clay, 1995; Odeh, 1999; Larinier, 2001, this volume). However, there is presently no single fish protection system or device which is biologically effective, practical to install and operate, and widely acceptable. Spill flows, as the simplest, can transport fish over the dam rather than through turbines or other discharges, but significant damage can occur. More sophisticated devices include highly engineered physical screening and behaviour-based guidance measures. Beginning in the 1990s, the use of Strobe lights (Martin and Sullivan, 1992), underwater electronically-generated sound (Loeffelman *et al.*, 1991; Dunning *et al.*, 1992), and the more economic Eicher fish screen showed potential for guiding fish more safely through, or away, from turbines (Adam *et al.*, 1991). Use of multiple, unequal sized turbines has been found to facilitate out-migration and reduce flow fluctuations below dams (Bowman and Weisberg, 1985).

Recently, progress has been made in improving fingerling by-pass facilities at small hydroelectric plants in France (Larinier and Travade, 1999), but research and testing continue. However, as the use of fingerling by-pass facilities is still in a more or less experimental stage, and until these facilities are installed at all dams in reservoir series, it may be necessary to enhance the passage of downstream migrants by induced spill of water at critical times. Further, increasing stream flows through water releases from upstream reservoirs during critical periods can allow or enhance downstream passage of drifting larvae or migrating juveniles by providing exogenous cues that trigger the onset of migration, quickening transport, providing guide flows, and maintaining suitable water quality (Karr, 1987; Berggren and Filardo, 1993; Karr *et al.*, 1998).

Increased spillage may be used to flush fish over a dam, or through a by-pass. These measures may be especially cost-effective when the downstream migration period of a target species is short, when migration occurs during high river flows and water would be spilled anyway, or when spill flows are needed for other reasons, (e.g. to increase dissolved oxygen concentrations or maintain minimum instream flows). Although costs of construction and labour are low for these mitigative measures, the real cost factor is the quantity of spill water that is not available for power production. Suitable discharges may be specified in the user's licence invoking the "User-Pays Principle" (cf FAO, 1997), or renegotiated

if the user's licence has to be renewed. As with any fish passage device, care should be taken to ensure that mortality associated with spillway passage does not exceed turbine passage mortality (see also Larinier, this volume).

Sluiceways or by-passes are used to transport fish downstream through the dam, either alone or, more commonly, in conjunction with some other mitigative measure such as screens. If fish tend to concentrate in the upper portion of the water column, they may use orifices or overflow areas leading to ice and trash sluiceways to by-pass the turbine intakes (Taft, 1990). Designing an effective by-pass for low-head dams can be relatively easy, given proper consideration of scale; Larinier and Travade (1999) provide several examples. However, at high dams or where debris or ice in the water are abundant, fish may suffer injury or mortality in the by-pass channel or pipeline. Criteria for designing effective by-pass systems have been described (Rainey, 1985; Clay, 1995).

A simple and common means of reducing fish passage through turbines is to modify the trash racks used to prevent large debris from entering the power-plant intake. One common modification is the angled bar rack, where the trash rack is set at an acute angle to the flow direction (rather than perpendicular to flow), and individual bars may also be set at an angle to the flow. Water entering the turbine must abruptly change direction as it passes through the angled bar rack. The belief is that fish can sense and avoid this change in direction of the bulk flow and will be guided downstream along the angled rack to a by-pass. Frequently, the bars within an angled bar rack are spaced more closely than in a conventional trash rack; spacing between the bars may be reduced from typical values of 8-20 cm, to no more than 2.5-5 cm. Closely spaced bars will prevent large fish from becoming entrained in the intake flow even if the behavioural guidance aspect of the device fails.

Travelling screens are also used to prevent fish from passing through the turbines. Vertical travelling screens are commonly used at steam electric power plant intakes and rotary drum screens are often used at irrigation diversions; these designs have also been modified for hydropower intakes. The most frequently studied travelling screens for hydropower applications are the gatewell screens installed at several dams in the Columbia River basin. These screens are installed in the upper portion of the turbine intake gatewell. Because some downstream migrating salmonids are surface oriented, they encounter the screen and are forced upward into gatewells, where they pass into a flume and are routed either to a collection point (for truck or barge transportation downstream) or are discharged into the tailrace to continue their downstream migration.

A variety of other fish screens have been suggested, but some are recent developments and few have received the extensive biological testing at hydropower plants that is needed to determine their general effectiveness. Inclined plane screens, vertical punched plate screens, and cylindrical wedgewire screens have been recommended (Dorratcague, 1985). One version of an inclined plane screen (known as the passive pressure or Eicher screen) has been installed in a penstock at the Elwha Dam in Washington State, USA. In this design, downstream-migrating fish can be diverted out of the penstock and into a by-pass. Studies of the diversion and survival of salmon smolts have been encouraging (Winchell and Sullivan, 1991).

Barrier nets have been tested, but have not gained wide acceptance (Taft, 1990). Deployment and maintenance can be very labour intensive. A mesh size sufficiently small to exclude a variety of fish species and sizes will also collect water-borne debris, thereby requiring cleaning and protection from wave action. Other mitigative measures depend on fish behaviour rather than physical screens to exclude fish from turbine intakes. Behavioural barriers that have been studied include electric screens, bubble and chain curtains, chemical repellents, underwater lights, and sounds. Although the results of studies of these measures have been equivocal (Mattice, 1990), some refinements of behavioural barriers continue to be examined.

The choice of mitigative measures is dependent on the species and behaviour of fish in need of protection. If the intent of the mitigation is simply to prevent resident fish from becoming entrained in the turbine intake flow, then a physical exclusion device (e.g. angled bar rack, cylindrical wedge-wire screen, barrier net) without by-pass facilities may suffice. If there is a need to transport downstream-migrating fish below the dam, then the mitigative measure must also incorporate some means of safely conducting the fish (e.g. through by-passes, trash sluices, collection and hauling). In such cases, not only the intake exclusion device but also the subsequent downstream transport measure must be evaluated for effectiveness.

2.5 The River Downstream

2.5.1 Practices to Restore or Maintain Aquatic and Riparian Habitat

Several options are available for the restoration or maintenance of aquatic and riparian habitat. One set of practices is designed to augment existing flows that result from normal operation of the dam. These include operation of the facility to produce flushing flows, minimum flows, or turbine pulsing. Another approach to producing minimum flows is to install small turbines that operate continuously. Installation of re-regulation weirs in the river downstream can also achieve minimum flows. Also, riparian improvements are important and effective in restoring or maintaining aquatic habitat.

Flow augmentation procedures such as flow regulation, flood releases, or fluctuating flow releases all have a detrimental impact on downstream aquatic and riparian habitat, but can be managed to enhance downstream conditions. A flushing flow is a high-magnitude, short-duration release for the purpose of maintaining channel capacity and the quality of in-stream habitat by scouring the accumulation of fine-grained sediments from the streambed. Flushing flows wash away the sediments without removing the gravel (unless excessive), and prevent the encroachment of riparian vegetation. Routine maintenance generally requires a combination of practices including high flows coupled with sediment dams or channel dredging, rather than simply relying on flushing or scouring flows (Nelson *et al.*, 1987). Minimum flows are needed to keep streambeds wetted to an acceptable depth to support fish. Because wetlands and riparian areas are linked hydrologically to adjoining streams, in-stream flows should be sufficient to maintain structure and function of wetland or riparian habitat. Flushing and scouring flows may also be necessary to clean some streambeds, flood wetlands, and to provide the proper substrate for aquatic species.

Seasonal discharge limits can be established to prevent excessive, damaging rates of flow release. Limits can also be placed on the rate of change of flow and on the stage of the river to further protect against damage to in-stream and riparian habitat. Several options exist for establishing minimum flows in the tailwaters below dams (see 2.5.3). Sluicing (releasing water through the sluice gate), turbine pulsing (releasing water through the turbines at regular intervals), and small turbines (capable of providing continuous generation of power using small flows) have been used to improve flows. Re-regulation weirs installed in the streambed below the dam to capture hydropower releases can also regulate flows (Nestler *et al.*, 1986) to produce desired water level and velocities (and to improve dissolved oxygen, as discussed earlier).

Riparian and in-stream improvements are another strategy that can be used to restore or maintain aquatic habitat. Riparian improvements may often be more effective than flow augmentation for protection of in-stream habitat (Swales, 1989). In general, improving riparian vegetation and providing greater habitat diversity are the most effective strategies (Andrews, 1988).

2.5.2 Release Patterns

The physical, chemical, and biological characteristics of reservoirs are generally intermediate between those of a river and those of a lake (Thornton *et al.*, 1990). Operation of reservoirs strongly influences

their effects on the river downstream, and can alter the ecological structure within the reservoir. Releases are perhaps the most ecologically significant aspect of reservoir operation (Straškraba, 1999), including: (i) quantity and rate of water releases, that also affect residence time; (ii) timing of releases; and (iii) depth from which water is released which affect stratification in the reservoir and water quality downstream and in the reservoir.

Dam release patterns may be classified either as run-of-the-river or storage-release. Run-of-the-river dams typically use little or no storage volume, and tend to operate more closely to the natural flow patterns of the river. However, in some cases flow in the river bed may be reduced or eliminated by re-routing it through pipes that carry water to turbines. These reservoirs seldom have the problems associated with hypolimnetic releases described earlier, and have limited disturbances to sediment, nutrient, and seston transport. Conversely, storage-release reservoirs withhold flow for irrigation, water supply, navigation, flood-control, or hydroelectric production, and thereby alter daily, seasonal, and annual patterns. Pulsing releases, such as those resulting from hydropeaking for energy generation, typically produce the largest environmental alterations downstream. Storage-release reservoirs change the river's sediment, nutrient, and seston transport functions, and alter water quality.

2.5.3 Hydrological Effects

Flow variability controls all physical, chemical, and biological phenomena in a river. Impoundments, particularly those of storage-release nature, reduce the annual variability of flow, although hydropower impoundments may increase diel variability. Without established minimum flows, storage-release reservoirs may virtually stop flow for hours, days, or even weeks. Some hydropower dams have underground power stations, resulting in the desiccation of a section of the river directly downstream from the dam. Resident fishes experiencing flow alterations may be affected for great distances downstream. Flow modifications affect water quality, water depth and velocity, substrate composition, food production and transport, stimuli for migration and spawning, survival of eggs, spatial requirements and eventually fish species composition (Petts, 1984). Mitigation techniques for flow alterations include construction of re-regulating weirs (Shane, 1985), low level releases to maintain negotiated minimum flows, and manipulation of cross-sectional stream geometry. However, all these generally lead to reduced variability, whereas in nature unpredictable flows seem to produce diverse communities, as flow conditions favour different organisms.

Minimum stream flows historically were set based on some hydrologic character of the river (e.g. percentage of mean annual flow). However, low-flow recommendations are often deleterious to fish and fisheries. Improvements to establishing minimum flows include Tennant's (1976) method, wetted perimeter curves (Hauser and Bender, 1990), habitat retention models (Nehring, 1979), and a physical habitat simulation model (PHABSIM; Bovee, 1982). In general, these methods vary flow to provide suitable habitat year-round. However, many methods exist for determining minimum flow regimes (see reviews by Trihey and S. Stalnaker, 1985; Morhardt and Altouney, 1985; and Estes and Orsborn, 1986).

Flow augmentation through seasonal releases of water from storage reservoirs, can facilitate movement of fish migrating upstream or downstream, and inundation of the floodplain. Often, upstream storage reservoirs can be managed for, or their operation coordinated to provide, flow augmentation. Thus, water from reservoirs positioned high in the watershed may be released during spawning periods or periods of low flow to improve flow and flooding and improve downstream habitat conditions and fish passage. Methods for improving habitat, other than flow augmentation, are reviewed by Swales (1989) and Orth and White (1993).

2.5.4 Release Level

The physical, chemical, and biological attributes of the downstream ecosystem are dictated by whether releases are drawn from the hypolimnion, epilimnion, or from multi-levels (Cassidy, 1989). Depth of

withdrawal affects water temperature, levels of dissolved gases, nutrients, turbidity, passage of toxic or oxygen-demanding materials, and biotic assemblage and diversity. Hypolimnetic releases are relatively cold, oxygen depleted, nutrient-rich, and may have high concentrations of iron, manganese, and hydrogen sulfide (Petts, 1984). Epilimnetic releases are typically less disruptive as temperature and water quality characteristics are more suitable to the downstream biota. However, because reservoirs cool and warm more slowly than streams, normal seasonal temperature patterns may be delayed by as much as 20-50 d in some latitudes (Crisp, 1977). If the reservoir constitutes a nutrient trap, reduced nutrient discharges contribute to reduced productivity downstream. Selective withdrawal over a range of depth allows for matching releases with the dynamic conditions downstream. Nevertheless, multi-level discharges may be less desirable for hydropower producers because all available head may not be usable.

2.5.5 Release Standards

Environmental problems as a result of low dissolved oxygen (DO) may be widespread in highly impounded river systems. Although releases are aerated downstream, the length of the downstream section impacted by low DO depends upon quality of the release, turbulence, and photosynthesis and respiration. Depending on these variables, as much as about 70 km may be required before oxygen tension rises to satisfactory values (Fish, 1959), about 5 mgL⁻¹ (Coble, 1982), although this target concentration varies depending on the fish assemblage (e.g. warmwater versus coldwater). In cascades of reservoirs, low DO in one reservoir may even affect lake and release DO in another. Thus, artificial re-aeration (Bohac *et al.*, 1983; EPRI, 1990) through selective withdrawal, destratification, oxygen injection, turbulence-production, sluicing, or hydroturbine aeration (Bohac *et al.*, 1982, 1983) is critical in many situations.

Manganese and iron are the two metals most often associated with releases. Both metals become soluble in water in an anoxic hypolimnion and are highly toxic to fish (Doudoroff and Katz, 1953), but rapidly oxidize when DO increases to >0.2 mgL⁻¹. Oxidized precipitates of these metals may physically damage fish. Grizzle (1981) reported effects of manganese on fish such as destruction of gill epithelium causing respiratory difficulties and suffocation; accumulation in internal organs; lesions on gills, liver, spleen and kidney. These oxidized metals also affect consumption of water by municipal and industrial users as they stain plumbing and laundry, affect taste and odour of water, and interfere with manufacturing processes. The effects of manganese and iron are significant only at concentrations greater than 1 mgL⁻¹ (Gordon, 1983). Practices that improve hypolimnetic DO levels in reservoirs also lower manganous and ferrous ion levels. Mitigation efforts may include changes in the release regime that allow minimal or calculated discharges of hypolimnetic waters, and rescheduling of outages that require sluicing to cooler times of the year when DO is higher.

Hydrogen sulfide may reach toxic concentrations in releases and the reservoir. It occurs in the anoxic hypolimnion and accumulates as a result of metabolic reduction of sulfates by anaerobic bacteria. Concentrations >0.002 mgL⁻¹ have offensive odour and may cause fish kills. This level has been established in the USA as constituting a long-term hazard to most fish and aquatic life (USEPA, 1986). Practices that improve hypolimnetic DO levels in reservoirs also reduce levels of hydrogen sulfide.

Supersaturation of gases (mainly nitrogen) in releases may occur from artificial aeration of the hypolimnion, cascading spillway discharges, or through discharges of turbines operating at low generation levels. Supersaturation is aided by rapid pressure decreases and rapid temperature increases. This supersaturation of water with gases is only temporary, but return to equilibrium may often take long, and thus supersaturation can occur in tailraces. At high levels dissolved N cause fatal gas bubble disease (Bouck, 1980). A maximum saturation value of 110% total dissolved gases, at the existing atmospheric and hydrostatic pressures, is generally considered adequate to protect salmonid and other fishes (Ruane *et al.*, 1986). Supersaturation in waters passing over spillways may be reduced or eliminated by spillway

design (Smith, 1976), and in turbines by modification of air-valve systems (Ruggles and Watt, 1975), placement of perforated bulkheads in turbine bays (USACOE, 1979), or use of degassing siphons (Monk *et al.*, 1980).

2.5.6 Effects on Abiotic Environment

Reducing water flow changes the landscape downstream (Simons, 1979; Reiser *et al.*, 1989). Reductions in sediment loads caused by impoundments, prompt the river downstream to try to recapture its load by eroding the downstream channel and banks. River beds are typically eroded by several meters within a decade of dam construction; this change can extend for many kilometres below a dam, depending on the slope of the terrain. River bed deepening can also lower the water table along a river, threatening vegetation and local wells in the floodplain and requiring crop irrigation in places where there was previously no need. The depletion of river bed gravels reduces habitat for many fish that spawn in the gravelly river bottom.

Channel degradation processes such as bank scouring, straightening, and deepening induced by high-speed releases usually dominate below dams, with rates of erosion typically higher than those associated with unimpounded rivers (Petts, 1984). Turbidity may be due to bank erosion, sluicing of sediments from the reservoir, annual uprooting of aquatic plants, or even unusually high primary production in the reservoir. The U.S. Environmental Protection Agency recommends that light penetration should not be increased by 10% over the unaltered stream, Hynes (1970) concluded suspended solids levels $>80 \text{ mgL}^{-1}$ were likely to be harmful to aquatic life, and Cairns (1968) discussed more specific standards. Scouring of the tailwater persists until the channel has modified itself enough so that flow velocities fall below the threshold for transfer of streambed sediments. Degradation may be slowed by riparian vegetation, large channel cross-section, channel slope reduction, and the presence of streambed materials too large (e.g. boulders) or too cohesive (e.g. bedrock) for flow to remove.

Alteration of channel morphology and sedimentation by releases generally results in loss of habitat heterogeneity and smothering of the benthic community. Accumulation of coarse sediments on riffles, and filling of pools effectively destroy spawning, nursery, and shelter habitat of fish (Petts, 1984; Welcomme, 1985; Nelson *et al.*, 1987). Gross substrate deposition and transport are detectable and documentable by grading with numerical substrate codes (e.g. Brusven and Rose, 1981). These methods classify substrates into size categories, and rate of change is measured through periodic classification (USEPA, 1985).

2.5.7 Effects on Biotic Environment

Tailwaters immediately below dams are usually autotrophic because the reservoir accumulates nutrients originating from the watershed above the dam. However, when the discharge is nutrient-rich with a relatively low level of turbidity, production of algae may be stimulated. Farther downstream, as the river becomes more heterotrophic, photosynthesis and primary productivity will be reduced to play only a limited role. Tailwater periphyton remove nutrients from the flowing water, and serve as food for zooplankton, benthos, or various fish species. Macrophytes in the tailwater are limited to littoral areas and relatively stable pools. Because tailwaters are dynamic with respect to depth and discharge, they do not provide suitable habitat for most higher plants; however, areas that are subject to frequent inundation may support bryophytes. The sediments in most tailwaters are composed of grains coarser than those in the reservoir and usually will not support rooted aquatic plants (Petts, 1984; Orth and White, 1993).

Release patterns and quality affect downstream biota in numerous ways (Gore and Petts, 1989; Welcomme, 1985; Cheslak and Carpenter, 1990). Large flow variations may adversely affect

downstream productivity by impacting spawning and disrupting benthic populations. In addition, cooler releases slow chemical and biological reactions, thus reducing productivity in the affected reach. The macroinvertebrate and fish species are typical of the natural stream system, but community structure depends on reservoir operation such as duration and quantity of low-flow releases, flood releases, etc. Although lower nutrient concentrations in releases can result in lower primary production in the tailwater, the export of reservoir plankton can compensate for this reduction by supplementing the food supply for the macroinvertebrate and fish species. Conversely, nutrient-rich releases stimulate increases and even lavish development of periphyton, algae, and macrophytes. The benthic community may shift towards grazers and collectors and experience loss of diversity as organisms depending on thermal cues for spawning, hatching, and emergence will dwindle. Large diurnal flow fluctuations can have a deleterious effect on many macroinvertebrate and fish species. While the diversity of species generally decreases, those species that are able to tolerate the large flow variations can become abundant. Macroinvertebrate densities also may increase markedly during the initial downstream water surge at the start of the generation period. Macroinvertebrate transport is greatest during generation, but many of these invertebrates may originate in the reservoir and are transported into the tailwater, supplementing the food supply for the tailwater fisheries. Non-generation periods may strand some fish and macroinvertebrate species and result in their desiccation. Assessments of effects on fish communities may be quantified using methods such as the Index of Biotic Integrity (Karr *et al.*, 1986).

2.6 Multiple Reservoir Systems

Water release patterns are a central feature in the ecology of impounded systems, and when reservoirs are constructed in series, the potential for controlling timing, volume, and quality of releases is maximized. Nevertheless, the interactions that occur among the reservoirs in a series vary depending on the characteristics of individual reservoirs. Basin morphology, reservoir siting, and release features and patterns determine the interactions among the reservoir series. Factors such as bottom releases into a shallow reservoir or surface releases into a deep reservoir will drive abiotic and biotic characteristics in the series. Nevertheless, the ecological structuring and functioning of reservoir series are poorly understood, and thus their ecological impacts and benefits are hard to manage.

2.6.1 Water Quality

Major changes in water quality and phytoplankton assemblages were noted in a cascade of seven large reservoirs in the Tietê River, downstream from São Paulo, Brazil (Barbosa *et al.*, 1999). Much of the nutrient and sediment loads were absorbed early in the cascade, particularly in the first reservoir. In this manner, the reservoirs located higher in the cascade contributed to improved DO, reduced turbidity, and overall better water quality in succeeding reservoirs. However, a proliferation in downstream eutrophication is forecasted as reservoirs high in the cascade become hypereutrophic and their ability to store nutrients diminishes.

System regulation for quantitative aspects, such as flood-control and hydropower generation, is a widely accepted and established practice, and the same principle applies to water quality concerns. Water quality maintenance and enhancements may be possible through coordinated system regulation. This applies to all facets of quality, from the readily visible quantity aspect, to traditional concerns such as water temperature and dissolved oxygen content. System regulation for water quality is of most value during low-flow periods when available water must be used with greatest efficiency to avoid degrading reservoir or river quality. Seasonal water control plans are formulated based on current and forecasted basin hydrologic, meteorologic, and water quality conditions; reservoir trophic status; water quality objectives; and knowledge of water quality characteristics of component parts of the system. Required flows and qualities are then apportioned to the individual projects, resulting in a quantitatively and qualitatively balanced

system. Computer programs capable of simulating reservoir system regulation for water quality provide useful tools for deriving and evaluating water control alternatives.

2.6.2 Cumulative Impacts

An issue likely to influence the weighing of benefits and problems of reservoir development is that of cumulative impacts. Cumulative impacts can occur over a large geographical area, over a long time frame, can be the direct or indirect effect of an activity, and can occur in an additive, synergistic, or threshold manner. Cumulative impacts can be caused by dissimilar activities or projects in the same general areas, or by different activities resulting from a single project. Thus, although an individual project may have no substantial adverse effect on the fish and fisheries of a river basin, the cumulative effect of such development throughout the river basin could be quite harmful, particularly to migratory fish. Because cumulative impact assessment involves estimating the combined effects of all past, present, and reasonably foreseeable future actions, cumulative impacts have been very difficult to assess and are generally ignored.

Synergistic relations are potentially very important. Of particular concern is the potential blockage of migratory routes caused by the construction of several dams. Of equal importance are the effects of turbine-induced mortality and predation at hydroelectric sites during downstream migration. Fish that survive turbine passage may be weakened. If given time to recover, fish could continue their downstream migration. Similarly, fish passing directly through the tailwater avoid predation and proceed downstream safely. But fish that are delayed in the tailwater due to stunning during turbine passage are more subject to predation and experience higher mortality rates. For example, chinook salmon (*Oncorhynchus tshawytscha*) runs originating in a river in Idaho, USA, must pass eight main-stem dams on the Snake and Columbia rivers. If we assume an average mortality at each dam of 15%, then 73% of the original stock is lost through the eight passes. Ascension up these rivers to the spawning grounds is accomplished on a tight energy budget, and each fish uses its remaining body reserves to spawn. If upstream passage requires more energy to overcome repeated man-made obstacles, a fish's energy reserves may become depleted before spawning.

Cumulative impacts are difficult to assess. However, a matrix technique has been used successfully to assess basin-wide impacts. The matrix lists proposed and existing hydroelectric projects and components of the resource that can be affected. The matrix cells are assigned a number that represents the relative magnitude of the project's impact on the resource. Some impacts may be very detrimental to the resource, while others may be less damaging because they are temporary or uncommon. Thus, each impact is weighed differently and combined into a single weighed mean, which represents the potential overall impact of the project on the fisheries resource. Because development occurs on streams with different capacities to support fish populations, projects with similar design and operational modes affect the basin's fish population differently. Thus, the weighed means may be adjusted to incorporate some indication of the value of the resource potentially impacted. An example of this approach is given by (Cada and McClean, 1985).

2.6.3 Need for Comprehensive Models

The rationale of managing reservoirs on a basin-scale instead of on a project-by-project basis rests on the recognition that the water and land resources of a basin form a unity, and hence must be treated as such if aquatic resources are to be preserved. River basin management and planning for a basin may broadly be conceived as an attempt to identify the best possible utilisation of the available water resources given existing hydrology, land characteristics and use, dam engineering features, and concerns about the biodiversity and fisheries. Due to the multitude of water resources development options that often exist, conflicts over the utilisation of a particular source between individual schemes and the interdependency between water and land use, river basin management is indeed a complex

task. The management of a reservoir within a multiple reservoir basin requires consideration of aspects about water management elsewhere in the basin. One of the major constraints to sound fisheries development in three different Asian basins was identified to be the lack of a coordinating river basin authority (Petr, 1985).

Currently, no single technological tool, model, or set of management strategies can address all components of a river basin. The ability to develop integrative management plans on a river basin scale is particularly limited for biological components. Various water resources models capable of undertaking an integrated analysis have been developed (reviewed by Lee and Dinar, 1995); unfortunately, they generally ignore biological aspects. An exception is a model derived for the Columbia River system, USA. This model uses a system of penalty functions to define the economic, social, and environmental cost of deviating from ideal operation (USACOE, 1994).

2.7 The Backlash on Estuaries

A river's estuary is a particularly productive ecosystem. They support the richest fisheries in the world and have substantial influence on marine ecosystems (Oglesby *et al.*, 1972; Wiley, 1976). Outflows into the oceans and seas control salinities, turbidities, and nutrient levels in estuaries. Fisheries in estuaries depend on the volume and timing of nutrients and fresh water. By interrupting downstream transport of nutrients, reservoirs may drastically affect the amount and timing of organic resources available downstream. These changes can restructure biotic communities and fisheries. Declines of the pelagic fishery of the entire Eastern Mediterranean Sea have been traced to nutrient trapping by Lake Nasser reservoir (Halim *et al.*, 1995). Reductions in nutrients due to dams on the Danube, Dnieper, Dniester, and Don rivers in Europe have been associated with reductions in fisheries in the Black Sea and Sea of Azov (Tolmazin, 1979; Volovik, 1994). A similar decline occurred in water quality and fishery production in the Caspian Sea after construction of a series of dams on the Volga River (Carre, 1978). Such effects have also been noted elsewhere in the world, including the Gulf of California and San Francisco Bay in North America, and the Oosterhelde estuary in Europe (Nienhuis and Smaal, 1994). Aside from reducing nutrient loadings, reservoirs redistribute annual patterns of discharges and temper their variability, changing the timing of nutrient availability and levels of salinity, and diluting their intensity. These changes can modify the composition of fish assemblages attuned to seasonal flow dynamics, and harm fishery yield.

Moreover, inhibition of sediment transports by dams contributes to extensive losses of wetlands. Reservoir storage in the upper Columbia and Snake rivers, USA, has altered both the seasonal pattern and the characteristics of extremes of fresh water entering the estuary. Since large-scale regulation of the flow cycle began about 1969, the variation of monthly mean flow has been reduced. Flow damping has resulted in a reduction in average sediment supply to the estuary. Between 1870 and 1990, due in part to sediment input reductions, the estuary of the Columbia River lost 8 000 ha of tidal swamps, 4 000 ha of tidal marshes, and 1 200 ha of tidal flats. This has resulted in an estimated 80% reduction in emergent vegetation production and a 15% decline in benthic algal production (NRC, 1996). Vörösmarty *et al.* (1997) estimate that at the global level 16% of sediments are already trapped by dams.

Mitigation of such large-scale environmental effects is daunting. Releases from dams may be modified to more closely parallel natural discharges relative to timing and nutrient and sediment loads. Extensive impoundment of river basins should accommodate reduction in estuarine fisheries and mitigate by encouraging stepped-down fishing fleets and providing relief to the ensuing social and economic impacts. Water and energy conservation guidelines and standards should be developed and implemented in the basin; savings from conservation programmes should be used to restore optimum stream flows. Options for dam removal should be pursued where feasible, to return downstream reaches to conditions more similar to environmental baseline conditions.

3. GUIDANCE AND CRITERIA FOR MANAGING FISH STOCKS AND FISHERIES

3.1 Fish Responses to Impoundment

An unavoidable effect of impoundment is a shift in species composition and abundance, with extreme proliferation of some species and reduction, or even elimination, of others (Agostinho *et al.*, 1999). The level of impact on the biological diversity is greatly influenced by the characteristics of the local biota (e.g. reproductive strategies, migratory patterns), characteristics of the reservoir (e.g. morphology, hydrology), design and operational characteristics of the dam, and characteristics and uses of the watershed (e.g. forestry, agriculture, mining, industries, urbanisation). Generally, the response of the fish assemblages to impoundment is a chaotic succession of reactions marked by a reduction in the established interdependence among species, and a lower biotic stability, deranging continuity of the biota and natural succession processes (Wetzel, 1990). These conditions limit organisms that participate in the rapid initial succession to those which enjoy broad physiological tolerances and behavioural adaptations. Impoundment reduces the cyclic nature of the riverine environment by restraining natural hydrologic cycles, and may introduce non-cyclic perturbations related to operation of the dam, exacerbating the instability induced by the foreign environment. The biotic community responds by reducing species diversity and becoming gradually simpler, a response evident during the first few years after impoundment. These responses are aggravated by catalysts such as unsuitable water temperature, low dissolved oxygen, low habitat diversity, inadequate or few spawning sites, absence of suitable food during at least some stage of ontogeny, absence of shelter for prey, and exclusion through interspecific interactions (Paller and Gladden, 1992).

Reservoirs have fostered replacement of unique stream faunas by fishes adapted to the new environmental conditions in the more regulated stream or reservoir environments (Zhong and Power, 1996). Moreover, impounded waters have often been managed by introducing species better adapted to lacustrine environments. Introduced species often out-compete native species, leading to replacement of the native fauna. In general, shallow reservoirs located in warm latitudes usually have resulted in an increase in total fish biomass over that of the free-flowing streams (Jackson and Marmulla, 2001, this volume). In deep reservoirs or colder latitudes, however, population abundances have declined (Ebel, 1979; Jackson and Marmulla, 2001, this volume).

There are about 800 species of freshwater fishes in North America (Canada, United States, and Mexico). Of these, 103 fish taxa were considered endangered, 114 threatened, and 147 of special concern (Miller *et al.*, 1989). During the twentieth century, 27 species and 13 subspecies have been reported as extinct. These extinctions have occurred primarily in western North America and the Great Lakes region. The most common cause of extinction has been habitat loss, a contributing factor for at least 73% of the 40 taxa. The second most common causal factor was the effects of introducing non-native species (cited for 68% of the 40 taxa). Other factors cited included chemical alteration or pollution (38%), and overexploitation (15%). None of the extinctions has been attributed directly to construction of dams.

Changes in habitat caused by dams often limit the lotic fish fauna to the upper, unimpounded reaches of streams. Because the reservoir acts as a barrier for dispersal, preventing upstream or downstream passage, these populations often remain isolated. These small and fragmented populations may survive for many years in a river basin, but much of the original genetic variation may be lost (Wilson, 1988). Lack of passage also restricts the ability of fish to recolonize suitable habitat following catastrophic events. Thus, dams have fragmented the home ranges of certain species, causing local extinctions.

Biodiversity in impounded rivers may be promoted by encouraging preservation of sections of the river in near-pristine conditions. Further investigation is needed to determine whether conservation efforts

should focus on maintaining many small preserves, or a few large ones. Additionally, introduction of species non-endemic to the river basin to increase fishery production should be weighed very carefully or simply avoided (see 3.2.2).

3.2 Fish Assemblage Management

3.2.1 Composition of Fish Assemblages

Fish assemblages in reservoirs are the result of a restructuring of those communities that previously occupied the dammed river, its floodplain and associated lakes. The riverine species composition varies greatly among zoogeographic regions (Matthews, 1998), with some regions containing a larger proportion of species pre-adapted to occupy lentic reservoir environments. Restructuring is marked by local extinction of some components of the original fish community and by drastic alterations in the abundance of most species (Agostinho *et al.*, 1999). Reservoir characteristics may restrict or promote adaptations that are successful in enhancing fitness of a species in the riverine environment. Only those species with adaptations (perhaps mainly feeding and reproductive) that fit the available habitats will successfully colonize a reservoir. The absence of pre-adapted lacustrine species has been associated with reduced fisheries yield in reservoirs of Southeast Asia and South America (Fernando and Holčík, 1982). However, in reservoirs of the Upper Paraná River basin, Brazil, the absence of pre-adapted lacustrine species appeared to be symptomatic of unsuitable environment (Gomes and Miranda, in press, b). The physical characteristics of reservoirs in the Upper Paraná River basin, exacerbated by climatic patterns, seemed to preclude the emergence of successful reservoir species from within the extant pool of riverine species. The resulting assemblages had characteristics that were neither riverine nor lacustrine, and were maladapted to support fisheries in the reservoirs. Introduction of lacustrine species generally failed because environmental characteristics were not lacustrine, except in reservoirs positioned high in the basin where increased retention time allowed lacustrine conditions.

3.2.2 Stocking and Introductions

Fish stocking is perhaps one of the oldest management practices. It has been controversial because in many instances it has disrupted fish communities, contributed to the loss of wild strains, and reduced genetic diversity (Schramm and Piper, 1995). Nevertheless, stocking has a significant role in reservoir management when used in the right manner and in the right location. If reproductive success is limited by the absence or poor quality of spawning habitat, stocking of juveniles can supplement those produced naturally, thereby increasing fish abundance and fisheries yields. Populations of many anadromous species are often heavily supplemented by stocking. Some fish populations in reservoirs are maintained solely by stocking because reproduction cannot occur within the reservoir environment. Stocking to restore threatened and endangered species has been successful in many instances. Size of fish stocked is often an important consideration, with fish survival increasing directly with size, but adequate success is sometimes obtained by mass stocking of undersized fish (Welcomme and Bartley, 1998). Economics often dictate the size and quantity of fish stocked.

Many reservoirs provide the opportunity to diversify fish stocks available to fisheries. Various non-native prey and predator species have been introduced into reservoirs with mixed success (Balayut, 1983; Schramm and Piper, 1995; Cowx, 1997; Quiros, 1998; Petr and Mitrofanov, 1998.). The native fauna inundated by the reservoirs is often not well adapted to function in lentic or limnetic habitats. Predator introductions have been stimulated by a commonly occurring excess availability of prey species in limnetic areas of reservoirs, the need to establish new fisheries, and the need to spread fishing effort over several species. Prey introductions have generally been stimulated by the need to provide suitable-size prey to predators, inasmuch as many of the prey species that thrive in reservoirs often grow too large to serve as prey. Where the fisheries are maintained largely to produce food, such as in most developing countries, quick growing, self-propagating herbivores with short food chains are preferred (Sugunan, 1995).

Perhaps the most successful introductions, from a fishery development perspective, have been those of tilapias and clupeids. Various species of tilapia have been successfully introduced into reservoirs of Africa, Asia, and South America (Oglesby, 1985; Moreau and De Silva, 1991; Paiva *et al.*, 1994; Sugunan, 1995), and clupeids in Africa and North America (Jenkins, 1967; Kapetsky, 1986). Their introduction usually results in tremendous boosts to the fishery production in reservoirs that maintain lacustrine conditions with high water retention times, such as small reservoirs impounded in low order streams. In some African reservoirs stocking is conducted in nursery areas (Kapetsky, 1986). Nursery areas allow development of tilapia populations in a virtually predator-free environment, as predators are removed and fishing is prohibited. Nevertheless, introductions of tilapia have reportedly impacted native ichthyofaunas from India (Sugunan 1995), to Africa, and North America (Moyle, 1976). In reservoirs with rapid turnover rate, riverine limnological conditions tend to limit development of tilapia fisheries (Gomes and Miranda, in press, b).

However, in some occasions, introductions have done more harm than good (Li and Moyle, 1993); thus, several precautionary approaches have been proposed (Bartley and Minchin, 1996). Before initiating stocking or introduction programmes several issues should be carefully considered (reviewed by Cowx, 1998). Other management measures could achieve the fishery goals at lower cost, with longer-term benefits or with fewer disruptions of the existing biological community. The size and number of fish that need to be stocked influence whether the effort will be cost-effective and sustainable. How long the benefits will last is an important consideration; if stocking will need to be continued indefinitely, perhaps other enhancement measures may be more economical in the long term. The potential for adverse impacts to the environment and biota should be considered fully and efforts aborted if adverse impacts are foreseen. For this, an extensive knowledge should be acquired about the biology and ecology of the species candidate for introduction, and previous histories of introduction of the species or similar species should be carefully weighed. Introduction of migratory and predatory species should generally be avoided.

3.2.3 Controlling Undesirable Species

As a consequence of altering a stream to create a reservoir, the fish community is disrupted by the flourishing of some populations and the decline of others. The populations that flourish may sometimes become undesirable because they may interfere with production of desirable species. Various approaches have been used to control undesirable species (Wiley and Wydoski, 1993; Karpova *et al.*, 1996; Meronek *et al.*, 1996). These include selective poisoning, extreme water drawdown, selective harvesting, disruption of spawning behaviour and reproduction, increased predation, and barriers to prevent immigration. Species labelled as undesirable vary around the world. For example, in North America removal of large catostomids has been attempted through experimental commercial fishing programmes in reservoirs where recreational fishing for predator species constitute the most important fisheries (Wiley and Wydoski, 1993); conversely, in India removal of predators has been an objective where survival of commercial species is impeded by predators (Sugunan, 1995). Nevertheless, fish control programmes have had mixed results.

3.3 Managing Harvesting Systems

Successful development of reservoir fisheries depends on access to fishing sites. Fishery improvement programmes must consider facilitating access to the reservoir through suitable roads and boat ramps, as well as access to the fish through preparation of fishing sites to allow effective use of fishing gear (Karpova *et al.*, 1996). Such enhancements require long-term maintenance commitments.

Fishing mortality can have a major effect on the numbers, size, growth, and productivity of a fish population, and thereby influence the structure and function of a fish community. Fishing regulations, fisher education, and control of access to the fishery are the primary means of

controlling fishing mortality. Problems have resulted from both over-fishing and under-fishing. Often, many problems associated with fishing mortality can be controlled by inviting fishers to participate in the decision process. Amarasinghe (1988) demonstrated how fishery regulations imposed by the Sri Lankan government on artisanal fisheries could be effectively implemented only through fisher participation.

Regulations can be implemented with biological and sociological objectives. Protection of stocks from overfishing, and from reduction to levels inadequate for successful reproduction, has historically been the major biological objective of fishing regulations. However, as the dynamics of fish populations and communities have become better understood, regulations have also been used to enhance stocks. Fishing can be regulated to adjust size composition of stocks to influence prey populations through top-down processes. Sociologically, regulations have been used to distribute fish more equitably among fishers, to provide fishers with a valid expectation of fishing success, and to reduce conflict among different user groups.

Many types of regulations have been applied to fisheries in impounded rivers (Welcomme, 1985; Noble and Jones, 1993). Licenses and permits have been used to control fishing effort and generate revenue to administer fisheries programmes. Size limits, including minimum, maximum, and protected size ranges, have been used to protect portions of populations, alter population size structure and community composition, and produce quality recreational fisheries. Creel limits have been used to divide harvest equitably among fishers and prevent overexploitation. Gear restrictions have been used to reduce or increase efficiency in both commercial and recreational fishing, to protect selected segments of fish populations, and in the case of recreational fisheries to increase the variety of fishing experiences. Closed seasons have been imposed mainly to prevent harvest of spawners. Closed areas have been used to protect fish that tend to concentrate (e.g. for spawning) in certain regions of a reservoir, or to protect fishers from competing uses of the reservoir. Zoning of reservoirs has sometimes been used to segregate commercial from recreational fishers, or fishers from other boaters (e.g. skiers), and thereby minimize conflict (Jones, 1996).

3.4 Aquaculture in Reservoirs

Cages have been used to produce commercial aquacultural crops within the reservoir and in the heated effluents of power plants. Growth and survival of fish is affected by the density of fish per cage, the density of cages per unit of volume, the species of fish cultured, and the quality of the feed. In China, culture of silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*H. nobilis*) fingerlings is conducted in cages without supplementary feed (Lu, 1986). Problems associated with cage culture include biological fouling of the mesh material, loss of fish to predators and disease, poor water quality, theft and vandalism, loss of cages during severe weather, deterioration of cage materials and conflict with navigational and recreational uses of public waters (Beveridge and Stewart, 1998).

In 1985-1988 the Saguling and Cirata hydropower reservoirs in West Java, Indonesia displaced over 40 000 families. As part of a comprehensive resettlement plan, an attempt to employ 3 000 families (1 500 in each reservoir) in floating fish cage aquaculture was attempted. Over a 4-year period aquaculture research, demonstration, extension, and training programmes were conducted. By 1992, fish cage aquaculture and other aquaculture support systems in and around the Saguling and Cirata reservoirs employed 7 527 persons. At the end of 1996, total aquaculture production was nearly 25 000 metric tons (approximately 95% *Cyprinus carpio* and 5% *Oreochromis* spp.). Total 1996 gross revenue from fish was about US\$24 million, over twice the estimated annual revenue from the 5 783 ha of rice lands lost to the reservoirs (Costa-Pierce, 1998).

However, guidelines set on the numbers of cages (10 600 in Cirata and 5 800 for Saguling) to protect the environment were not enforced, and thus cage culture has taken a toll on the environment. Fish cages

tended to develop haphazardly in very few areas of the reservoirs where market access was good, rather than where the environments were suitable, further degrading the aquatic environment. As a result of overcrowding and water column turnovers, there were numerous, large fish kills in the upstream Saguling reservoir, and fish cage aquaculture production dropped. Thus, while reservoir cage aquaculture developments were very successful from a fish production viewpoint, aquaculture has not been environmentally sustainable. In general, floating net cage aquaculture can be used as a sustainable enterprise in reservoirs only if adequate training for reservoir aquaculture is provided to prospective culturists, and there is adequate enforcement of regulations on cage numbers to prevent environmental degradation.

3.5 Improving Infrastructure and Marketing

Improved infrastructure is needed to prevent or limit post-harvest losses in developing countries (e.g. Jhingran, 1992). Facilities must be adequate for landing, chilling, storage and processing of fish and for distribution. Inadequacies in these facilities and in arrangements for distribution cause the most visible post-harvest losses, particularly of fresh fish. For example, many of the small pelagic species in African reservoirs could become sources for direct human consumption if suitable processing facilities and knowledge were available. Lack of control of oxidation and microbial contamination prevent the use of these species more widely as food or food ingredients. They are currently used largely as raw material for fish meal and fish oil production.

Increasing commercial values of the existing yield, without actually increasing yield, may be an option to enhance the standard of living for fishers. Commercialisation schemes often involve middlemen that enjoy most of the profits from the fisheries. In reservoir fisheries of the Paraná River, Brazil, middlemen pay about US\$0.50 per kg of fish and sell it for up to US\$2.00 to the markets (Agostinho *et al.*, in press). In some cases the middlemen support the fishers by providing fishery equipment, health assistance, and buying the production even during periods of low fish demand. Nevertheless, better organisation of the fishers into co-operative groups, subsidized initially by government organisations, might provide a more stable market, allow fishers to retain a larger fraction of the profits, and improve their quality of life. In China, reservoir fish are commonly marketed at purchasing stations established by a government agency (Lu, 1986).

Another major problem concerns the disposition of unintended landings. A high proportion of the catch may consist of edible species, which are sometimes discarded or have low value for lack of suitable technology and marketing arrangements. An effective way to reduce losses from this source would be to avoid taking non-targeted species. Alternatively, fishing techniques and markets may be developed to use other components of the fish assemblage. All species available in reservoirs are seldom adequately used, in part because of cultural reasons, alternative markets are not available, or simply because adequate fishing gear has not been developed. For example, the piranhas (*Serrasalmus* spp.) are caught with gill nets in South American reservoirs, but are not commercialized because they have many small bones, and the public is afraid of their ferocity. In addition to increasing fishery yield, exploitation of piranhas may help control their abundance and lead to a reduction of attacks on netted fish that damage gear and quality of landings (Agostinho *et al.*, 1997). Other species may not be used because they are considered “too ugly” by consumers. Still in other cases, religious constraints may constrain fishery development such as in some Asian reservoirs (DeSilva, 1985). The exploitation of minor cyprinids was found to be commercially feasible in Sri Lankan reservoirs (Sirisena and DeSilva, 1988). Education and marketing may make some species more available and desirable in some markets.

3.6 Gaining Institutional and Political Recognition

An important barrier to reservoir fisheries development and management is that fishery administrators find it difficult to defend the interests of their sector whether recreational or, worse,

commercial fisheries. Decisions over developments affecting fisheries and aquatic environments are often made with minimum or no consideration of these sectors, mainly for lack of reliable economic valuation and lack of political clout by the users. In countries where inland fisheries management is integrated within organisations that manage forestry, wildlife, or agriculture, inland fisheries management invariably receives low priority (Sugunan, 1997). Most policy makers are not aware of the importance of inland fish production for food supplies and livelihood. In developed countries, however, anglers are often well organized and more able to influence the political decision process; yet, their demands may take a backstage because of their recreational nature. In a number of developing countries most reservoir fisheries suffer from the absence or inadequacy of defined rights and institutional support, resulting in difficulties in obtaining political and financial support for monitoring and managing fisheries. Given this lack of political power, the interests and needs of fishers and fisheries managers are often not properly represented within existing political frameworks, and thus neglected or ignored.

Fishery administrators and stakeholders should seek every opportunity to communicate their needs, demonstrate the value of fisheries and the aquatic natural resource integrated by fish, and participate in the political process. Fisheries agencies should place high interest on selling their programmes through one-way channels such as news releases, brochures, and magazine articles that serve to educate and communicate with the public, fishers and non-fishers (Addis and Les, 1996; Brown, 1996). Conversely, fishery managers need to seek public input through public meetings, surveys, and other mechanisms that allow feedback. Determination of the value of natural resources is becoming increasingly important in resource management. Specifically, this information can be used by the public, policy analysts, and public officials to allocate funding. Techniques for determination of economic value and impact of commercial and recreational fisheries have been developed and applied in the last 2-3 decades and are now readily available for most fisheries applications (see Talhelm and Libby, 1987, and articles in that volume). Open, responsive relations between managers and the public along with adequate estimates of resource value facilitate participation of fishery managers in the political arena, while maintaining an image of non-political, scientific professionalism.

4. IMPROVING GUIDANCE AND CRITERIA

4.1 Managing with Local Paradigms

Management of impounded river basins in many developing countries follows models developed in North America or Europe. Strategies are often imposed by foreign experts or copied, considering neither climatic, faunal, socio-economic conditions, nor political realities. Despite the apparent commonality in environmental issues, management policy must be country-specific, and take local conditions into account (Sugunan, 1997); blind application of imported principles leads to policy failures. For example, fish passage facilities have been legislated in some parts of Brazil, without regard for the characteristics of the basin or the nature of the ichthyofauna (Alzuguir, 1994). In one extreme case a fish ladder was mandated in a dam located upstream a 70 m waterfall in a river lacking migratory species (Agostinho, 1994). Fish hatcheries are often constructed along with dams, a trend initiated in North America in the 1940s when it was believed that reservoirs could not produce self-supporting fish assemblages (Miranda, 1996). Such facilities are sometimes constructed without first assessing whether supplemental stocking will be necessary, and with no information about the culture requirements of potential culture species, which may eventually lead to cultivating and stocking exotic species for which culture information is available. Although experience in other regions should not be ignored and should serve as the base for management plans, evaluation of strategies and revision to fit local realities are critical to successful adaptation and implementation.

4.2 Integrative Water Allocation Plans

A holistic approach to the management of fresh water as a finite and vulnerable resource must be taken, one that integrates economic, social, and environmental needs. Water allocation plans for river basins are essential to ensure that available water is adequately apportioned to meet this goal. The multi-sectoral nature of water resources development in the context of socio-economic development must be recognized, as well as the multi-interest use of water resources for water supply and sanitation, agriculture, industry, urban development, hydropower generation, inland fisheries, transportation, recreation, bottom-lands management and other activities. To this end, effective water management plans, coordination, and implementation mechanisms must be in place in all river basins.

Integrated water resources management is based on the fact that water is an integral part of the ecosystem, a natural resource, and a social and economic good, whose quantity and quality determine the nature of its utilisation. Water allocation plans must take into account the functioning of aquatic ecosystems and the sustainability of the resource; priority has to be given to the satisfaction of basic needs and the safeguarding of ecosystems. Integrated water allocation plans should be carried out at the level of the catchment basin or sub-basin, and consider land- and water-related aspects. Plans should focus on at least three aspects. Firstly, a plan should promote a dynamic, interactive, iterative and multi-sectoral approach to water resources management, including the identification and protection of potential sources of freshwater supply that integrates technological, socio-economic, environmental and human health considerations. Secondly, a plan must develop policies for sustainable and rational utilisation based on community needs and priorities within a conservation framework. Thirdly, projects and programmes should be both economically efficient and socially acceptable, and their design and implementation based on an approach of full public participation. Fish and fisheries management should be integral parts of such plans, and fishery administrators should work within existing framework to seek recognition for their programmes (see 3.6 and 4.4). An example of an extensive water allocation plan is provided by the Delaware River Basin Water Code (DRBC, 1996).

An example of this approach is provided by Lynch *et al.* (1999) for the Michigan Department of Natural Resources (MDNR), USA. The MDNR redesigned their boundaries for management units within their various branches (including fisheries, wildlife, forests, and recreation). The new boundaries were redrawn along river basin and ecoregion lines, from the previous political-boundaries approach. Then, instead of having each branch of MDNR develop management plans in isolation, the design and implementation of all management plans requires input and contributions from managers in all branches. Furthermore, each management plan is based and measured by local criteria, rather than by broad standards. Management is thereby more comprehensive and specific to a watershed or ecoregion. This approach, however, requires a great deal of communication, collaboration, and coordination among different branches of natural resources management agencies, which may at times be international.

4.3 Collaborative and Participatory Planning and Management

Decisions about the aquatic environments emerge through political processes. The ultimate source of these is the peoples' preferences, fishers or otherwise, and preferences reflect fundamental values and judgements. Environmentalists often argue that only zero risk is ethically and environmentally acceptable; however, they forget that ecosystems are extremely variable and forgiving and that virtually nothing has zero risk. In contrast, proposers of reservoirs frequently maintain that almost any level of risk is justifiable, if the economic benefits are substantial enough; however, they forget that not everything has a price. People need to make judgements that feed into the political process (Aguero and Lockwood, 1986).

Development of river basins, and specifically reservoir fisheries, raises a wide range of environmental, social and economic issues. Reservoirs are usually managed as common resource open to all, requiring

the balancing of user demands that often leads to conflict (Jones, 1996). Poor decisions that lack public acceptability, or are not based on proper analysis, can have serious impacts on the environment as well as economic and social well-being. Decision support through participatory management is therefore critical (Sugunan, 1997). The environmental assessment community is now taking on board participatory methods. Such methods bring together scientific and consultative approaches, accommodate the uncertainties and complexities of environmental issues, and include non-expert participants (Maine *et al.*, 1996). Scientific approaches include the use of formal frameworks such as cost-benefit analysis or risk assessment, which weigh different outcomes (Siri and Born, 1998). Consultative approaches include focus groups, citizen juries, and stakeholder decision analysis (Decker and Enck, 1996; Ewert, 1996). Pluralism and consensus are appropriate ways of managing aquatic environments from which people derive benefits. A diversity of choices, rather than single options, should be considered when reaching decisions.

4.3.1 The Maine Rivers Policy: an Example of Balanced Policy Development

In response to conflict between hydropower developers and recreational fishers the State of Maine, USA, developed an energy policy (MOER, 1982) and a rivers policy (MDC, 1985). The energy policy acknowledged the importance of hydropower to meet a portion of the State's energy needs, and called for the removal of unnecessary administrative obstacles that impeded the development of sensible hydropower projects. The rivers policy contained a statewide fisheries management plan, including a clear policy on fish-passage facilities at dams, and identified river stretches with outstanding natural and recreational values, and proposed a strategy for protecting these values.

The Maine rivers policy formed the basis for designating a portion of Maine's rivers for special protection. Such protection prohibited the development of new dams, and required that existing dams be redesigned to enhance, or at least not diminish, the natural resource. The policy also prohibited residential and commercial development near the banks of a river designated for special protection, although it allowed timber harvest and gravel operations under strict standards. Additional protection from incompatible shoreline development was given to other segments of Maine rivers, primarily near urban areas. Other river segments were made available for hydropower development with fewer restrictions. The environmental protection agency was given responsibility for inspection of dams, and for establishing standards for water level and water quality above and below the dams.

Many of the steps taken in Maine are readily adaptable elsewhere. The thread that unites the many diverse planning and implementation actions into the rivers policy is balance. The policy balances demands upon rivers, identifies the best uses for individual segments, and provides the means for resolving conflict. Without clear guidance about those rivers where hydropower is not desirable, developers no longer waste effort on projects that could never be built; with the policy in place, developers can now focus efforts on hydropower projects less likely to present insurmountable environmental problems.

4.3.2 Partnerships That Pay Off: TVA's Watershed Programme

The Tennessee River, USA, includes more than 30 major reservoirs operated by the Tennessee Valley Authority (TVA) for navigation, flood-control, power production, water quality, recreation, and other purposes. In 1991, TVA adopted a reservoir-operating plan that increased the emphasis placed on water quality and recreation (Poppe and Hurst, 1996). This plan modified the drawdown of ten tributary reservoirs to extend the recreation season and included a 5-year, US\$50 million programme to improve conditions for aquatic life in tailwater areas by providing year-round minimum flows and installing aeration equipment at 16 dams to increase dissolved oxygen levels. In 1992, to prevent these improvements from being negated by nonpoint pollution and to respond to growing public interest in water quality, TVA launched an effort to protect watersheds by forging alliances with governments, businesses, and citizen volunteers. The goal was to ensure that rivers and reservoirs in the basin were

ecologically healthy, biologically diverse, and supported sustainable uses. To accomplish this goal without regulatory or enforcement authority, TVA built action teams in each 12 sub-basins. These teams were responsible for assessing resource conditions and building partnerships to address protection and improvement needs.

The action teams represented a transformation of TVA's water management organisation from a hierarchy organized around technical disciplines to a dynamic organisation based upon cross-functional teams. These teams were unique in that they combined the skills of aquatic biologists, environmental engineers, and other water resource professionals with the skills of community specialists and environmental educators. Team members learned to communicate with the public in non-technical language and to build partnerships with farmers, waterfront property owners, businesses, recreation users, and local/state government officials. Assigning teams to a geographical area for the long-term allowed the teams to gain a better understanding of resource conditions, build community trust, and enhance the development of co-operative relationships with stakeholders. The teams were self-managed and empowered to decide how to focus resources and address protection and improvement needs, allowing a rapid response to evolving or newly discovered problems and opportunities.

The action teams assessed the health of rivers and their watersheds, using selected biological indicators that took a snapshot of the ecological conditions. Team members collected information about the number, type, and condition of the fish and benthic organisms, and analysed the data for clues about what is occurring in the watershed. They also examined existing data and sought input from resource users and other stakeholders. This information was used to decide where to focus team resources and to evaluate improvement activities.

The fundamental strategy of the teams was coalition building. Team members shared monitoring information with key stakeholders (e.g. regulatory agencies, state and local governments, businesses and industries, citizen-based action groups, and watershed residents) and sought their support in developing and implementing protection and mitigation plans. The challenge was to persuade potential partners that solving a given water resource issue was important to meeting their personal economic, social, and environmental needs, and the needs of their community.

Team efforts to build partnerships paid off. In 1995 volunteers contributed 22 500 hours in monitoring, habitat enhancement, cleanup, and protection activities. Acting as catalysts for change, action teams helped start or worked in partnership with many local coalitions to solve water quality problems; conducted over 400 stream and reservoir assessments; established 20 native aquatic plant stands in reservoirs; installed 4 500 habitat structures; stabilized shorelines; and implemented watershed management practices including construction of wetlands, fencing, and streambank revegetation. Team members also organized a variety of communication activities designed to educate people about water quality and involve them in solving pollution problems. By focusing on partnerships, action teams were able to accomplish more with less, while educating the public about environmental needs.

4.4 Resource Agency Participation in Reservoir Development

Agencies responsible for managing aquatic resources can increase their effectiveness in developing reservoir mitigation by fully participating in the development process. However, to effectively recommend mitigation procedures, agencies need to incorporate technical expertise in fields other than traditional fish ecology and management, coordinate among other agencies, be willing to make recommendations based on incomplete information, have procedural expertise, and develop effective policies (Railsback *et al.*, 1990).

Several agencies may be involved in reservoir development. For example, some agencies may be concerned about water quality while others about fisheries. Moreover, a waterbody may sometimes cross-political boundaries. The fewer policy conflicts and technical disagreements there are, the more authority the agency mitigation recommendations will have. Agencies should actively promote communication with other agencies as well as with the reservoir developer and their consultants. In many cases, agency biologists are expected to deal with complex issues such as hydraulics, hydrology, engineering, water chemistry, mathematical modelling, and fish physiology. Staff with traditional training may have difficulties developing evidence to support their mitigation recommendations.

Agencies may often be reluctant to make recommendations based on incomplete information, and instead tend to request additional studies. Some requests may be appropriate, but some may be requested even though they would be expensive and have low probability of success. Mitigation recommendations may often need to be made on incomplete information. Recommendations can use the best available data, professional judgement, conservative assumptions, safety factors, and post-project monitoring to ensure that resources are protected (see review by Hillborn and Peterman, 1996).

Clear and effective policies for reservoir development can enhance an agency's influence in developing mitigation. The more thoroughly an agency can back-up mitigation recommendations with established regulations, policies, and specific scientific objectives, the more influence the recommendation will have. Broad policy and goals must be transformed into clearly defined targets and objectives. For example, a recommendation that a hydropower project maintain pre-construction water quality is not an effective recommendation because it does not specify how pre-construction conditions are to be defined and measured, or whether this objective is technically feasible. Policies should be clearly defined but flexible enough to allow consideration of site-specific conditions. Mitigation recommendations should be technically defensible and implementable. Mitigation recommendations that would make a project uneconomical or infeasible should be avoided, unless the severity of the impacts justifies rejecting a project.

4.5 Periodic Project Evaluation

Licensing and relicensing may be used to ensure that reservoir construction and operation weights environmental concerns. Then, when deciding whether to issue or reissue a license, conservation, protection of fish and wildlife, fisheries, recreational opportunities, and preservation of general environmental quality benefits can receive equal consideration to energy or other economic benefits provided by impoundment. This equal consideration would require developers to develop licensing proposals in consultation with resource agencies including fish, wildlife, recreation and land management agencies, in order to assess more accurately the impact of impoundment on the surrounding environment. In this evaluation the licensing agency would be obligated to investigate reports which assess the environmental consequences of a proposed impoundment and compare the impacts with those of alternatives to the suggested action.

Dams constructed several decades ago were not built with a concern for protecting the river ecosystem. With the benefit of current social and scientific knowledge, however, many of the deleterious impacts on rivers caused by damming can be eliminated or minimized by changes in the operation of the dam. A relicensing process would provide an opportunity to modify dam construction and operation, and address environmental problems. Relicensing would also provide an important medium by which public interest issues related to river conservation can be addressed, as well as a means of ensuring that any chosen modifications, additions, or enhancements are expeditiously implemented (Hill, 1996; Harrel, 1996).

4.5.1 Licensing of Hydropower Dams: An Example from USA

In the United States, hydropower development is regulated by the Federal Energy Regulatory Commission (Hill, 1996). When considering licensing a new hydropower development (few new dams are currently being built in the U.S.), or relicensing an existing dam, the Commission has the responsibility to consider all aspects of the public interest and to license only those projects that are consistent with the best comprehensive use of the water resource. The Commission is obligated to give equal consideration to environmental resources and energy production. The Commission must carefully weigh competing uses to determine the best comprehensive development of the resource. Additional mandatory conditions may be imposed by certain resource agencies. Such plans may include, for example, a state restoration plan for some anadromous fish, a management plan for a national forest, or any other federal or state plan appropriately filed with the Commission. The Commission considers the consistency of a hydropower project with goals outlined in the plans, and heavily weighs such plans in any licensing decision.

A license applicant files a notice of intent to apply for a license about 5 years before the existing license expires, and files the application 2 years before the license expires. An applicant must follow a 3-step process that involves consultation with resource agencies and interested non-government organisations. In the first step, the developer meets with resource agencies and interested parties to review the project, identify environmental concerns, determine what studies may be needed, and develop mitigation measures. The second step includes completion of studies and consultation with resource agencies in developing a draft license application. Through these interactions the hydropower developer files a license application (step 3) that addresses the multiple uses of the resource, including mitigation. The Commission then reviews the application in consultation with all the interested parties. If the license is granted, the Commission monitors the project to ensure compliance with the terms of the license, and may take various enforcement actions if needed.

The trend is for a more inclusive and co-operative relicensing effort among interested parties that is commenced years in advance of the license expiration. In these co-operative processes, conservation groups, resource agencies and dam operators work together from the beginning of the relicensing process, jointly outlining studies, selecting contractors, and designing project operation and mitigation. The goals of this co-operative approach are to conduct environmental analysis early on in the relicensing process and, by developing consensus early about the needed mitigation, later avoid costly studies and delays.

4.6 Comprehensive and Integrated Monitoring Programmes

Ecosystems change over time, with or without human influence, due to climatic fluctuations. Human induced changes in river basins result from impoundment, introduction of exotic species, and alteration of the landscape through forestry, farming, and other developments. Sound management of impounded rivers depends on an ability to understand the effects of natural and human-induced change, which make management of impounded river basins extremely complex. Properly designed monitoring programmes that include repeated observations over time can separate natural effects from human ones, and distinguish effective management practices from less effective or harmful ones.

Monitoring programmes are needed to support a comprehensive, scientifically-based evaluation of the present and future condition of the environment and its ability to sustain present and future populations. Monitoring programmes should provide critical and timely feedback to managers. They should be designed to determine whether management actions are moving the ecosystem toward the goals and expectations. Monitoring is thus a means of checking on progress as well as a tool for improvement. Without it, there is no way of knowing if our management measures are working and how they should be changed to be more effective. Design, development, and maintenance of monitoring and evaluation

programmes require commitment and long-term vision. In the short term, monitoring and evaluation often represents an additional cost and is particularly difficult to maintain when budgets are tight and where personnel are temporary or insufficient. Yet, lack of consistent support for long-term monitoring and evaluation will hinder management. The information-base needed to manage impounded rivers (summarized by Bernacsek, this volume) should form the foundation for monitoring programmes. Guidelines for collection of fishery data and examples of monitoring programmes are provided by Gutreuter *et al.* (1995), USEPA (1998), and FAO (1999).

Management of aquatic resources is far from being a fully developed, predictable science. Much is not yet known about what the best indicators are, what are the most cost effective sampling designs, how to analyse the results to provide concrete information upon which to base management measures, and what management measures are most effective for the situation at hand. Thus, an effective monitoring programme is also critical to design and test management criteria within the context of an adaptive management framework.

4.7 Improving Criteria and Guidance through Adaptive Management

Impounded rivers are complex and dynamic ecosystems. As a result, our understanding of impounded rivers and our ability to predict how they will respond to management actions is limited. Together with changing social and economic values, these knowledge gaps lead to uncertainty over how best to manage impounded rivers. Despite these uncertainties, reservoir managers must make decisions and implement plans. Adaptive management (Holling, 1978; Walters, 1986; Parma *et al.*, 1998; Shea *et al.*, 1998; Callicott *et al.*, 1999) is a way for reservoir managers to proceed responsibly in the face of such uncertainty. It provides a sound alternative to either charging ahead blindly or being paralysed by indecision, both of which can foreclose management options, and have social, economic and ecological impacts.

Adaptive management may be particularly valuable for testing, refining and improving reservoir management criteria (see example by Lorenzen and Garaway, 1998). Although management criteria are based on the best available information and expertise, it requires reservoir managers and workers to implement many new, previously untested strategies. Managers are faced with questions such as: How do I implement the guidelines in a way that will meet management objectives? Which of several possible actions should I implement? There are also uncertainties about whether specific guidelines provide adequate protection for non-fishery values, and whether others place unnecessarily tight constraints on riverine habitat modifications. Adaptive management offers a way for addressing these questions. Adaptive management is a formal, systematic, and rigorous approach to learning from the outcomes of management actions, accommodating change and improving management. It involves synthesising existing knowledge, exploring alternative actions and making explicit forecasts about their outcomes. Management actions and monitoring programmes are carefully designed to generate reliable feedback and clarify the reasons underlying outcomes. Actions and objectives are then adjusted based on this feedback and improved understanding. Adaptive management views management not only as a way to achieve objectives, but also as a process for probing to learn more about the resource or system being managed; thus, learning is an inherent objective of adaptive management. As we learn more, we can adapt our policies to improve management success and to be more responsive to future conditions.

There are six main steps in adaptive management (Figure 1): step 1, problem assessment; step 2, design; step 3, implementation; step 4, monitoring; step 5, evaluation; and step 6, adjustment. The framework formed by these six steps is intended to encourage a thoughtful, disciplined approach to management, without constraining the creativity that is vital to dealing effectively with uncertainty and change. The details of how the steps are applied and the level of rigor used depend on the problem and on the imagination of the managers.

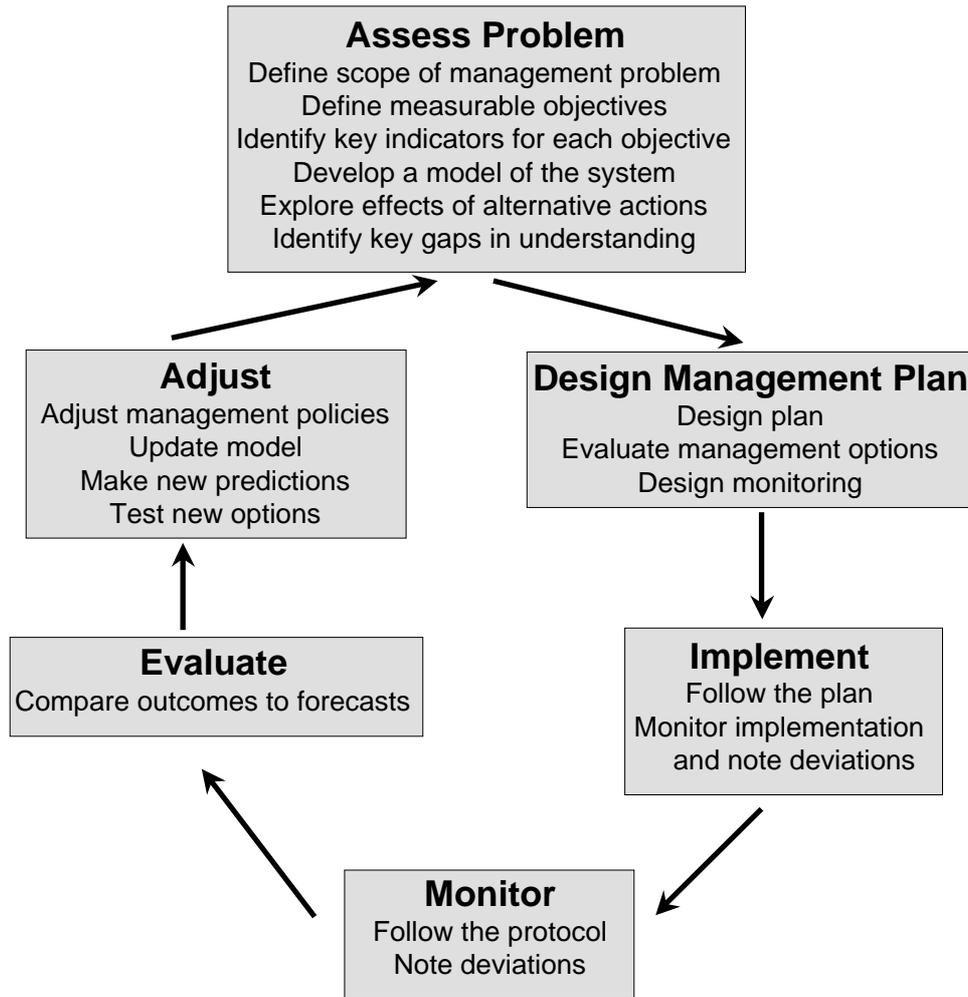


Figure 1. Framework for adaptive management

Step 1 (problem assessment) is often done in one or more facilitated workshops. Participants define the scope of the management problem, synthesize existing knowledge about the system, and explore the potential outcomes of alternative management measures. Explicit forecasts are made about outcomes, in order to assess which actions are most likely to meet management objectives. During this exploration and forecasting process, key gaps in understanding of the system (ie those that limit the ability to predict outcomes) are identified. Step 2 (design) involves designing a management plan and monitoring programme that will provide reliable feedback about the effectiveness of the chosen measures. Ideally, the plan should also be designed to yield information that will fill the key gaps in understanding identified in Step 1. It is useful to evaluate one or more proposed measures, on the basis of costs, risks, knowledge it generates, and ability to meet management objectives. In Step 3 (implementation), the plan is put into practice. In Step 4 (monitoring), indicators are monitored to determine how effective actions are in meeting management objectives, and to test the hypothesized relationships that formed the basis for the forecasts. Step 5 (evaluation) involves comparing the actual outcomes to forecasts and interpreting the reasons underlying any differences. In Step 6 (adjustment), practices, objectives, and the models used to make forecasts are adjusted to reflect new understanding. Understanding gained in the each of these six steps may lead to reassessment of the problem, new questions, and new measures to try in a continual cycle of improvement.

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ENVIRONMENTAL ISSUES, CAPACITY AND INFORMATION BASE FOR MANAGEMENT OF FISHERIES AFFECTED BY DAMS

by

**Garry M. Bernacsek
Fisheries and Environment Specialist
Global Aquatic Corporation Pty. Ltd.
45 Birchgrove Rd, Balmain NSW 2041
Sydney, Australia**

EXECUTIVE SUMMARY

Fisheries management capacity and information base requirements are reviewed for the six phases of the dam project cycle: dam identification; dam design; dam project appraisal; dam construction; dam operation; and dam decommissioning.

Fisheries management as applied to dams is perceived to be problematic and difficult due to the severe changes in hydrology and the impacts on fish that occur.

Dams impact fish *directly* by blocking or creating hazards to migration in upstream and downstream directions, and by mortality or damage when fish pass through dam discharge structures.

Dams impact fish biodiversity, fish stocks and fisheries *indirectly* by modifying and/or degrading the upstream and downstream aquatic environments, including: thermal stratification of the reservoir and release of cool and anoxic hypolimnion water downstream; downstream flow alteration and termination of inundation of downstream floodplains; sediment and nutrient trapping in reservoirs; release of contaminants from trapped sediment into the reservoir food chain; infestation of the reservoir with floating aquatic plants; ghost fishing by nets snagged on drowned trees in the reservoir; long distance recession of the shoreline during drawdown; and pesticide contamination arising from agriculture on the reservoir drawdown zone.

Fisheries management objectives in relation to dams include conventional management objectives: prevention of loss of endangered and/or commercially important fish biodiversity; maintenance of fish stock abundance; sustainability of catch, employment and income; security of consumer food fish supply; and production of exportable fish products.

Fisheries management objectives specific to dams include provision of bypass facilities for upstream and downstream migrations, development of new fisheries potentials in reservoirs, and maintenance of biodiversity in impacted environments (affluent streams, downstream river, delta, estuary and sea).

During the Dam Identification Phase, community-based or user group fisheries management systems should be put into place in the impact area for commercial and recreational fisheries. An Initial Environmental Examination should be carried out. A data base should be assembled which provides basic information in as much detail as possible on the aquatic environment, fish biodiversity, fish migration, existing fisheries upstream and downstream, likely impacts of the dams, and possible mitigation measures.

During the Dam Design Phase, community-based fisheries management should be continued from the previous phase. An Environmental Impact Assessment should be carried out. The information base required builds on that assembled under the previous phase but is much more detailed and comprehensive. The key output of the study is an assessment of the level of impacts on, and the risks for, fish and fisheries, as well as a statement with regard to the degree of suitability and acceptability - or need for rejection - of the project *from a fisheries point of view*. In addition, there should be given a set of mitigation measures and an environmental management plan, with recommendations for changes to the project for either of the following cases: a) the dam project is generally acceptable but changes would improve its environmental profile, or b) the dam project is adopted against the advice of the fishery sector to reject it. These changes should be incorporated into the final design of the dam project.

During the Dam Project Appraisal Phase, community-based fisheries management should be continued from the previous phase. During project appraisal, the worth of the project is examined. The key information required is contained in the environmental impact assessment and environmental management plans. A set of questions and criteria concerning the fisheries impacts and mitigations should be satisfied before approval for dam construction is given.

During the Dam Construction Phase, fisheries management activities need to be carried on which aim at preventing damage to fish biodiversity and fish stocks arising from construction activities. The main impacts are soil erosion and silt runoff into the river, siltation of key fish habitats downstream, blast damage from explosives and blockage of fish migration. Real time data is required during this phase. The management activities need to be rapidly responsive to the construction schedule. Special attention needs to be given to reservoir preparation with regard to clearing forests in a manner which will reduce problems of snagged nets and ghost fishing yet still allow sufficient surface area for periphyton growth for fish forage. Information needs focus on suspended solids, sediment transport, fish mortality, fish migration and fish biodiversity.

During the Dam Operation Phase, the needs for fisheries management of four impact areas must be addressed: 1) the reservoir and its affluent streams, 2) the fauna passage facilities, 3) the downstream river channel and floodplain(s), and 4) the delta, estuary and adjacent sea.

Reservoir fisheries management concerns focus on protecting spawning grounds in affluent inflow areas, stocking with indigenous and non-indigenous fish species to increase production, development of a small pelagics fishery, and management of the water level to prevent erratic behaviour deleterious to fish stocks.

Management of the fauna passage facility includes monitoring of fish traffic in terms of species, numbers, length/weight range. An assessment should be carried out of the efficiency of the fishpass in providing an access route for individual species, and appropriate adjustments made to the structure to improve its efficiency. The overall impact of the fishpass on reservoir fisheries and downstream river fisheries should be determined.

Downstream river fisheries management concerns focus on aeration of anoxic discharge water from the dam, provision of effective fishpasses to allow broodstock and juveniles to migrate across the dam, reduction of turbulence in the stilling pool, and mitigation of fish losses on the floodplain. The release of artificial mini-floods and the provision of adequate dry season flow are crucial to maintaining a suitable environment for migratory fish species, especially endangered species.

Fisheries management concerns for deltas, estuaries and the adjacent sea focus on changes in freshwater discharge and sediment/nutrient trapping in the reservoir which can be deleterious to certain fish stocks such as small pelagics and shrimp.

Information base requirements during dam operation consist of two types: 1) conventional fisheries management data used to assess catch and effort, and 2) data on fish biodiversity, fish stocks and environmental parameters to assess the impact of the dam and the efficiency of mitigation measures. Data should be incorporated into dynamic fishery models whose outputs can be used by dam operators in water management control models.

During the Dam Decommissioning Phase, fisheries management should focus on rapid recovery of fish stocks that have suffered impacts during dam operation. Measures should be implemented to prevent damage to fish stocks during dam demolition as well as enhancement measures, e.g. river rehabilitation, for the aquatic and related terrestrial environments. Fish biodiversity and migrations, as well as sediment loads, should be carefully monitored. Conventional community-based fisheries management should be continued.

Some aspects of regional characteristics for different dam types are reviewed. Dams are constructed for diverse purposes including hydroelectricity generation, irrigation, flood control, navigation, drinking and industrial water supply, fish production, and recreational fishing and boating. Effective environmental assessment and management coupled with improvements in design of civil engineering structures has made some recent dam projects more fish friendly and environmentally acceptable.

The legal framework for fisheries management related to dams is complex. It embraces laws and regulations governing various sectors, including water resources, environmental assessment, fisheries management, biodiversity conservation, forestry management and pesticides. There is a need to draft legal instruments which will facilitate modification of dam structures to incorporate mitigation measures and alter dam operation rules that would be beneficial to fish biodiversity and fisheries. Legislation should also require the use of a fraction of dam revenue for environmental research and mitigation, and oblige dam owners to implement beneficial mitigation measures.

The criterion 'no loss of biodiversity' is proposed as a goal towards which all dam projects should strive.

1. INTRODUCTION

Fisheries management as applied to dams, and the fish stocks and aquatic environments affected by dams, is a subject fraught with difficulties. It is a complex endeavour as it involves conventional fisheries management activities associated with regulating fishing effort and maintaining stock abundance, as well as various types of civil engineering constructions and manipulation of the aquatic environment. In the past, fisheries management concerns have typically received only modest attention in terms of research budgets, importance as a selection criteria for dam design alternatives (or project alternatives), and mitigation of negative impacts on fish biodiversity, fish stocks and fisheries. Happily, this situation has improved since environmental impact assessment (EIA) became universally mandatory for most types of dam projects. Important advances in management approaches and engineering of mitigation measures have resulted in new dam projects becoming more environmentally friendly than in the past (see Colt and White, 1991, for examples).

But significant technical shortcomings still exist with regard to fisheries management concerns in the project cycle, and there are major negative impacts for which consistently effective mitigation measures have not yet been devised (Roberts, 1995). Some of these issues (blockage to fish migration, efficiency of fishpasses, reduction in floodplain fish production) have a daunting quality. An intractable pessimism has emerged among many fisheries and environmental specialists on the feasibility of ever being able to mitigate these impacts, leading to a lobby for a moratorium on all dam construction in the future. In recent years, progress has been made in the general social and economic theory of fisheries management, particularly the conflict between resource users and remote centralized government management authorities. This has resulted in greater involvement of fishing communities in management of the resource in various forms such as co-management, self-management and private ownership. But problems remain, including unevenness in implementation and approaches world-wide, and difficulties with resolving major outstanding issues on resource ownership, access and enforcement authority.

Dam planning, construction and operation is one of the most information-intensive of all civil engineering projects, and typically employs a wide range of specialist skills. Because of the complexity of operation and diversity of impacts of dams, responsible and well behaved projects generate an information and professional capacity demand which extends far beyond purely engineering, hydraulic and hydrological skills to embrace sociological, environmental and economic disciplines. Of concern in this paper is the information base that is required to effectively manage the fisheries sector throughout the various phases of a dam project cycle. Rational decision-making about matters related to management of fisheries affected by dams should be based on comprehensive and high quality information. A poor quality information base will not likely lead to outcomes favourable to the fisheries sector.

The purpose of this paper is to review what type of information related to fisheries management is required at each phase of a dam project, and what fisheries management capacities are required to ensure that effective mitigation measures are implemented at dam projects, that new fisheries development opportunities are realized, that fisheries achieve sustainability, and that fish biodiversity is protected throughout the project cycle.

This paper is produced as a desk study based mainly on published articles and consulting reports. It also draws on the experience of the author on dam fisheries in Africa and Asia. There exists a rather copious literature on fisheries management in dams and their reservoirs at the global level. It is not possible to review this literature comprehensively in a paper such as the current one. Some illustrative examples are provided to support the arguments presented in the text, while references to key documents will allow readers to pursue important topics in more detail. Relevant examples are also to be found in other papers in this volume.

2. MAIN IMPACTS OF THE DAM PROJECT CYCLE ON FISHERIES

The dam project cycle consists of six major phases (see World Bank, 1991a: 2-3, for discussion):

1. Dam Identification Phase
2. Dam Design Phase
3. Dam Project Appraisal Phase
4. Dam Construction Phase
5. Dam Operation Phase
6. Dam Decommissioning Phase

The Identification, Design and Appraisal Phases are essentially planning and approval phases and are not accompanied by any major civil engineering activities in the field which have negative impacts on fisheries. Thus there are no special fisheries management operational needs over and above those measures applied in the unregulated river. However, these phases are information-intensive due to environmental assessment activities, and are crucial for generating the information needed to meet the objectives of fisheries management if the dam is eventually built, or for supporting a decision to abandon the dam project for environmental reasons.

During the Construction Phase, the main potential environmental impact on fisheries originates from soil erosion and silt runoff into the river due to clearing and excavation activities. This impairs water quality and can lead to acute or sublethal toxicity to fish. There is also danger of siltation of key fish breeding, nursery or overwintering habitats in the river. Another hazard to fisheries originates from the use of explosives. Blast shocks may cause lethal or sublethal damage to fish stocks. Blockage to fish migration is usually not a problem at dam sites where topography allows the excavation of a temporary bypass channel for river discharge. However, the constrained topography of dams situated in narrow river gorges will not allow excavation of bypass channels for river discharge, and diversions tunnels excavated in the cliff walls are used to conduct river water away from the dam foundations excavation area. Water velocity, tunnel gradient and hydraulic jumps may create fish-unfriendly conditions and effectively block upstream migrations of fish.

It is during the Dam Operation Phase - which can typically span 50 to 100 years - that the most severe impacts on fisheries and aquatic environments take place. Petts (1984) and Welcomme (1985) produced comprehensive reviews of dam impacts on fisheries and aquatic ecology at global level, while Bernacsek (1984a; 1997a) carried out detailed analysis of the impacts of dams on aquatic environment and fisheries in Africa and South-east Asia. Impacts can be grouped into two categories: 1) impacts which affect fish directly, and 2) impacts which affect the fisheries environments (upstream river, reservoir, downstream river, estuary, delta, sea) in some manner that leads to a deterioration in fish biodiversity, fish stocks and/or fisheries production.

Category 1 impacts include the following:

- The dam constitutes a barrier to upstream migration for almost all fish species. This prevents broodstock from reaching their spawning grounds during the breeding season, resulting in massive failure of recruitment and eventual extinction of the stock above the dam. Dams in coastal locations prevent fingerlings and juveniles migrating from brackishwater breeding and nursery areas from reaching freshwater habitats upstream, leading to similar impacts.
- Downstream migration past the dam may also be difficult or impossible for many fish species. Fish migrating into the reservoir from affluent streams may be unable to find their way to the dam site and subsequently downstream through discharge structures. This can affect spawning and recruitment.

- Fish passing downstream through discharge structures at a dam can suffer mortality or damage in a number of ways, including abrasion against rough surfaces, turbine blade mangling, rapid pressure changes, water shearing effects and nitrogen supersaturation in the stilling basin.

Category 2 impacts include the following:

- Thermal stratification of reservoirs during the warm season can result in deoxygenation of the hypolimnion. Cool and/or anoxic water discharged from the hypolimnion can severely reduce water quality downstream and negatively impact fish stocks and fisheries. Fish may be eliminated from the river as far downstream from the dam as deoxygenation persists.
- Dams with large storage reservoirs can produce abnormally low discharge flows in the downstream river channel, and reduce or eliminate inundation of downstream floodplains. The reduced water level and duration and area of inundation severely limit fish production. Fish biodiversity also generally suffers losses. In cases where hydroelectric dams have underground power stations and all river discharge is diverted to the power station, the intervening stretch of river may be permanently desiccated.
- Reservoirs trap sediments brought in by affluent streams. The turbidity of outflow water of the dam is usually low and there is no deposition of nutrient-rich sediment on the downstream floodplain or delta. This will reduce the fertility and productivity of downstream aquatic environments. The negative impact on fish production may in some situations be felt as far downstream as the estuary and adjacent sea.
- In the case of sediment release from the reservoir, turbidity can become very high which can create severe problems for the downstream fauna and flora.
- Sediments trapped in the reservoir may be contaminated with pesticides and industrial chemicals from catchment sources, and residues can enter the reservoir food chain and taint fish.
- Infestation of the reservoir with floating macrophytes can cause a decrease in water quality in the reservoir and in downstream discharge. This is typically initiated by the release of nutrients from drowned vegetation and soil, resulting in a trophic upsurge of primary production and proliferation of floating plants during the first few years after filling. Large mats of floating macrophytes can lead to deoxygenation and acidification of the water column. Under such conditions fish biodiversity and production is reduced with only air breathing species able to survive. Deployment of most types of fishing gear becomes impossible.
- In most reservoir, trees and brush are not cleared before first filling. Fishermen routinely lose large quantities of gillnets in drowned forests which continue to ghost fish and cause excessive fish mortality.
- Drawdown results in long distance recession of the reservoir shoreline of up to several kilometres in areas with gentle bottom gradients. This necessitates continuous movement of artisanal fishing camps in developing countries (or sport fishing docks in developed countries) to keep up with the receding shoreline during the drawdown period or to escape inundation by the advancing shoreline during the impounding period. Difficulty can also be experienced in transporting the catch across the exposed drawdown zone to roads for pick-up by traders. Siting of fishing villages only in shoreline areas with steep bottom gradients (where shoreline displacement is minimal) may necessitate long travel distances by boat on the reservoir to access some fishing grounds.
- In many reservoirs the moisture-rich drawdown zone is used for agricultural production. Usually pesticides are used to control pest infestation, and this results in contamination of reservoir fish, leading to a health hazard for consumers.

In most cases, the construction of a dam results in changes in fish biodiversity and stock abundance. Usually, the number of fish species declines. Stocks of long distance migrating species and fast flowing water species decline while stocks of pelagic species and species that prefer slow moving water (i.e. pre-adapted to lacustrine conditions) increase.

3. THE OBJECTIVES OF FISHERIES MANAGEMENT IN RELATION TO DAMS

There is a large amount of diversity in dam designs, dam operations, impacted environments and climatic zones worldwide. It is nonetheless possible to specify sets of fisheries management objectives that will apply to most dams. Objectives in relation to dams fall into two categories. There are conventional or normative management objectives, which are not unique to dam-impacted fisheries but apply to most fisheries throughout the world. These generally include some or all of the following:

1. To maintain stock abundance at high levels.
2. To reduce the risk of overexploitation and stock collapse.
3. To achieve sustainability of production of commercially important species.
4. To prevent the loss of fish biodiversity.
5. To maintain levels of employment and enhance incomes within the fisheries sector.
6. To supply domestic consumers with good quality fish at affordable prices.
7. To produce fish products for export.

Dams impose very specialized and rigorous conditions on fisheries and aquatic environments. Therefore a further set of dam-specific objectives may be formulated to support and elucidate the above general objectives. These include:

- A. To provide effective bypass facilities for fish (and other animals) migrating upstream across the dam.
- B. To provide safe and effective bypass facilities for fish migrating downstream across the dam.
- C. To develop the new fisheries potentials created in the reservoir of the dam.
- D. To maintain fish biodiversity and production in affluent streams entering the reservoir.
- E. To maintain fish biodiversity and production in the riverine environments downstream from the dam.
- F. To maintain fish biodiversity and production in the saltwater environments (delta, estuary and adjacent sea) downstream from the dam.

Achievement of all of these objectives is a difficult undertaking for most dams, and the degree of difficulty generally increases with increasing dam wall height. Sound planning of management strategies and operations, founded on a reliable and comprehensive information base, is essential for achieving successful outcomes.

4. DAM IDENTIFICATION PHASE

4.1 Fisheries Management Capacity Requirements

There is no intrusive civil engineering field activity under this phase, and therefore no impacts on fish biodiversity or fisheries. There is however a need to carry out conventional fisheries management to regulate fishing effort to avoid overexploitation of the stocks and protect biodiversity. Sound management would maintain the stocks of migrating fish species at a high level. Apart from the benefits accruing to the fishery, this would serve to demonstrate the importance of the migrating broodstock for the existing river fishery and justify management initiatives to conserve stocks during the project cycle. Even if a project is eventually shelved and the dam is never built, the benefits of sound management of the river fishery will still be apparent and worthwhile.

There is a general consensus among fisheries specialists that community-based systems are the most appropriate and effective for management of small-scale fisheries. For example, a participatory fisheries management programme has been proposed for the recently completed Theun Hinboun dam in Laos

(Phonvisay, 1997; Anon., undated). Approaches to community-based management of fisheries are presented by Scudder and Conelly (1985), Ruddle (1987), Asada *et al.* (1983) and Berkes and Kislalioglu (1989).

General guidelines for managing inland fisheries are presented in FAO (1997), and complimentary guidelines for small-scale fisheries are in preparation. Specific measures for river fisheries were reviewed in Welcomme (1985: 247-265), and include regulation of access, increasing the catch capacity of fishermen, closed seasons, fish sanctuaries, mesh regulations, gear prohibition, flow modification, fish shelters, spawning area improvements, fishpasses, introduction of new species, stocking, aquaculture, cage culture and rice-fish culture.

4.2 Fisheries Information Base Requirements

General information needs for conventional fisheries management were reviewed in FAO (1996b). These include data for catch and effort, numbers of fishermen and fisherwomen, numbers and characteristics of fishing vessels and fishing gears, stock assessment indices and stock status, biological and environmental parameters which affect fish stocks, socio-economic characteristics of fishing communities, market parameters, and conflicts within the fishery.

Within the dam project cycle, this phase encompasses the identification of a suitable dam site, and general studies related to dam construction and function, including among others the characteristics of the catchment hydrology (area, rainfall, discharge), hydraulic parameters at the dam site, reservoir morphometry (elevation, volume, area relationship), and potential yield for specified purpose (irrigation, electricity, water supply, etc). Various geotechnical studies are carried out at the dam site, and the preferred dam type is specified. Some indication of costs and benefits is also prepared.

At this early stage, planning for fisheries management in relation to the dam project should be at the level of an Initial Environmental Examination (IEE). The purpose of the IEE is to provide a general baseline assessment of the nature and value (*senso lato*) of fish biodiversity and fisheries in the project impact area, the type and severity of impacts that could be expected, and the possible mitigation measures that might be implemented. Virtually all dam projects will require a full and comprehensive Environmental Impact Assessment (EIA) if the project advances to the design phase. The IEE is therefore to be regarded as a useful interim environmental assessment exercise which provides the foundation and framework for a subsequent EIA. Examples of guidelines for IEEs and EIAs for dam projects are presented in reports of the World Bank (1991b; 1991c) and the Asian Development Bank (1993). EIA guidelines presented by the United Nations (1990) are especially detailed and include case studies as examples. Environmental Risk Assessment (ERA) from the perspective of fish stocks should also be carried out in association with the IEE (see Asian Development Bank, 1991, for detailed methodology), and further refined under the succeeding project cycle phases.

The IEE should identify and highlight the main fisheries and fish ecology issues associated with the proposed dam. These could, for example, include blockage of migration of an important commercial fish stock, loss of endangered species, drowning of a unique and precious ecological site such as a waterfall or whitewater rapids, endangering of the food supply of a brackishwater small pelagic stock, or risk of thermal and oxygen stress on sensitive endangered fish species below the dam.

The required fisheries information base for an IEE would consist of the following:

- Determination of the project impact area limits from a fisheries perspective.
- Location and general characteristics of important or precious fish habitats within the project impact area, including spawning areas, overwintering refuge habitats (such as scour holes in the river), floodplains, mangrove swamps, deltas and estuaries.

- Inventory of fish biodiversity, and associated aquatic plant and animal biodiversity relevant to fish biology and fisheries.
- General life history and annual behaviour cycle information on each species, correlated with events in the annual hydrological cycle.
- Migration behaviour of fish species (both long distance migrators and fish species that during certain phases of their life cycles depend on longitudinal movements along the stream continuum) within the overall project impact area, and specifically in the vicinity of dam site.
- Number of existing obstacles upstream and downstream, and their impacts.
- Status of fisheries in the project impact area, including employment, production, income, technology, processing, marketing and international trade.
- General morphometric characteristics of the reservoir (for dams that store substantial water volumes) and potential yield of fisheries that could develop.

Analysis of this information base would allow the identification of the major fisheries assets and determination of the main impacts of the proposed dam on these assets. The IEE should also indicate the general types of mitigation measures that might be used for each impact.

If the result of the identification phase is a judgement that the dam is likely to be sound and viable as a project, it will be added as a potential project to a sectoral portfolio (i.e. power sector, agriculture sector, water supply). Information on fisheries impacts would normally be included as an Annex to a more comprehensive multi-sector IEE report, which in turn would be attached to the main project identification document. This would ensure that a decision to advance the project to design phase would be taken with full awareness of the possible consequences to fish biodiversity, fish stocks and the fisheries sector.

5. DAM DESIGN PHASE

5.1 Fisheries Management Capacity Requirements

As for the Dam Identification Phase, no intrusive field activities are normally carried out under the Dam Design Phase, and therefore no impacts on fish biodiversity or fisheries take place. Community-based fisheries management as implemented under the previous phase should be carried forward to this phase. As the information base grows under IEE and EIA activities, appropriate adjustments should be made to management practices. There are also opportunities to test assumptions, to further strengthen community-based management structures, and to build a lobby for fisheries protection and conservation.

5.2 Fisheries Information Base Requirements

Initiation of the Dam Design Phase indicates that a particular agency has decided that the identified dam is the preferred solution to meeting a particular need (i.e. growing demand for electricity, increasing need for irrigation and for food production, increasing demand for potable water), and that there is a serious intent on the part of the dam proponent to proceed with construction. This phase is characterized by detailed dam site studies and hydrological modelling, as well as comprehensive analysis of demand for the dam's output (electricity, irrigation water, domestic water supply) and the economic viability of the project. Usually, a number of alternative sites and dam designs will be prepared and assessed, and a preferred design would be selected and further prepared to detailed construction-ready stage.

The environmental laws of most countries and the internal requirements of funding agencies normally require that a comprehensive EIA be carried out during the Dam Design Phase. This includes a range of

impact studies such as fisheries, sociology, wildlife, forestry and health. The objective is to analyse the impacts and mitigation measures of the preferred dam site and dam design, as well as the alternatives sites and designs, and recommend appropriate changes in order to optimize the project as far as possible. These changes should then be incorporated into the final design of the project (or if this is not feasible, a recommendation could be made to abandon the project on fisheries impact grounds). The process is very information intensive and time sensitive, and includes modelling, scenario analysis and decision-making. High quality information needs to be made available to the design team at appropriate time periods in order for the process to be successful. In the past, the quality of fisheries data has not always been adequate and predictive capability has been poor (Bernacsek, 1997a).

The required fisheries information base for an EIA is much more comprehensive and focused than for the IEE. It would consist of the following data groups:

- Comprehensive environmental baseline data, and analysis of historical hydrology and related data of relevance to fisheries: Reservoir morphometrics; contour mapping and substrate-type/vegetation mapping; number and characteristics of obstacles in the river upstream and downstream of the dam site; hydrological modelling and design rule curve analysis; limnological study of river over a minimum of one full annual cycle, but preferably two or more annual cycles.
- Comprehensive fish species inventory upstream and downstream of dam site to cover entire dam impact area: Life history profiles of each species; migratory behaviour and migration across dam site; spawning period and spawning habitat location; growth; feeding.
- Basin-wide ecological modelling of the river (upstream and downstream of dam site) and the reservoir (with and without dam): Emphasis on fish biodiversity and fish production, as well as related parameters such as fish food supply (plankton, plants, invertebrates, forage fish).
- Catch assessment and frame surveys of fisheries sector upstream and downstream of dam site: Detailed information on fishing effort and production, fish processing, marketing and economic benefits (income and employment); structure and effectiveness of current fisheries management practices (in river, at other dams in country, in country in general); fisheries legislation and enforcement capacity.
- Detailed information on all engineering works: Design and capacity of structures; operating rules (i.e. design rule curve) for various design alternatives.
- Analysis of feasible mitigation measures for negative impacts of dam (for various dam design alternatives): Drafting of fisheries component of overall environmental management plan.
- Analysis of feasible fisheries enhancement measures: Pattern of clearing of trees and bush in reservoir basin to benefit fisheries; introductions and stocking; location of fisheries infrastructure and fishing communities in reservoir.

Certain aspects of project design could require exhaustive analysis and feasibility or pilot studies. Fishpass design is a major concern. A substantial literature exists on this important but difficult subject, for example Natarajan and Sehgal (1981), Pavlov (1989), Quiros (1989), Katopodis (1990), Indo-Pacific Fishery Commission (1991), Larinier *et al.* (1994), Clay (1995), Pholprasith (1995), and Odeh (1999). Two important international symposia were held in Gifu, Japan, during the last decade on fishpass design (Anon., 1990; 1995a) which allowed a substantial comparison of recent experiences at global level. It is clear that the single most important reason for failure of bypass facilities at dams is incorrect choice of fishpass design, followed by under-design (typically too steep a bed gradient) in order to economize on construction costs. The latter is particularly unfortunate, given that fishpass projects can have very robust internal rates of return, which would give considerable leeway for increasing expenditure to build a less steep and more fish-friendly structure. The need for bypass facilities may not be restricted to fish, but could also include such flagship species as river dolphins (Reeves and Leatherwood, 1994). Comprehensive study of the river fauna is therefore essential.

Forecasting the types of fisheries that will develop in the new reservoir is of importance. Various methods have been devised for predicting the potential fisheries yield of reservoirs (see for example, Henderson and Welcomme, 1974; Bernacsek and Lopes, 1984a; Marshall, 1984a; Moreau and de Silva, 1991; Chookajorn, 1992; Crul, 1992; Bernacsek, 1997a). These methods usually give reasonable ballpark estimates but may not be reliable for guiding management decision with regard to investment, quotas or reference points. Littoral fisheries develop as a matter of course based on fish species present in the river. The development of a small pelagics fishery is generally desirable, and will depend on the presence of suitable fish species (which can be either indigenous or introduced). Analysis of reservoir morphometry will indicate the relative extents of the littoral and pelagic zones (Bernacsek, 1984a: 41-42).

Cumulative impacts on fisheries need to be analysed on a river basin-wide basis, for example, for a cascade of dams (Hill and Hill, 1994), or for dams in association with other types of industrial development within a basin (Bernacsek, 1981). The case studies presented in Petr (1985) clearly indicate the need for comprehensive cross-sectoral basin-wide planning for multiple resource use situations.

Substantial professional expertise in fisheries is required to carry out a full EIA, including fisheries biology, ichthyology, limnology, and fisheries economics. The fisheries team would require access to expertise in hydrology, hydraulic engineering and dam design engineering. The hydraulic engineer should have comprehensive expertise in fishpass design and construction, and should collaborate closely with the fisheries biologist who should have sound knowledge of fish biology, swimming behaviour and fish ecology as well as practical experience with fishpass design and monitoring.

The key fisheries outputs during the Dam Design Phase are a comprehensive set of mitigation measures that are to be incorporated into the final dam design, and an environmental management plan for the subsequent dam construction and operation phases, which includes comprehensive monitoring of impacts and mitigation efficiency, as well as contingency plans for residual impacts and risks. The EIA should present an assessment of the level of impacts on, and the risks for, fish and fisheries, as well as a statement with regard to the degree of suitability and acceptability - or need for rejection - of the project *from a fisheries point of view*. Fisheries specialists should be prepared to suggest changes to dam design in order to reduce environmental impacts. For example, changes beneficial to fisheries were incorporated into the final design of the Pak Mun dam in Thailand as a result of environmental assessment (World Bank, 1994). If the dam project is generally acceptable but changes would improve its environmental profile, recommendations for such improvement should be incorporated into the dam design. If the advice of the fisheries assessment is to abandon the project, but the project is subsequently adopted against this advice, these changes should be incorporated into the final design of the dam project.

An important objective of the final dam design (which would then progress to the appraisal phase) is that it should be fully optimized, as far as is technically possible, to incorporate solutions to all fisheries and environmental concerns. All necessary and feasible mitigation measures should be built into the design. This can only be achieved through close collaboration between fisheries, environmental and engineering personnel in the design team. The environmental/fisheries specialists are to be integral members of the design team and carry out their activities as merged components with engineering and hydrology, and not as separate studies. As well, fisheries and environmental considerations should be acted on very early in the project cycle, during identification (as IEE) and design (as EIA). Any approach that regards mitigation measures as add-ons to solve environmental problems once the dam has been appraised and approved is quite inefficient and not likely to result in an environmentally friendly dam.

The EMP that is appended to the design should include contingency measures for any impacts that could not be mitigated in the dam design by the environmental/fisheries specialists. The EIA should clearly state what impacts are residual and do not have a technical fix. The principal manner of addressing these residual impacts is to rely on contingency measures (which may or may not be successful in coping with

the problem, and therefore contain a high level of risk), or to decide that the project is too risky and should not go ahead because of the unmitigatable residual impacts. The task of the next phase in the dam project cycle (Appraisal) is to take that decision: Is society prepared to accept the risk of a probable loss in fish biodiversity and fisheries production, or will it abandon the dam?

6. DAM PROJECT APPRAISAL PHASE

6.1 Fisheries Management Capacity Requirements

As for the previous two phases, no intrusive field activities are normally carried out under the Dam Project Appraisal Phase, and therefore no impacts on fish biodiversity or fisheries take place. Community-based fisheries management should continue under this phase.

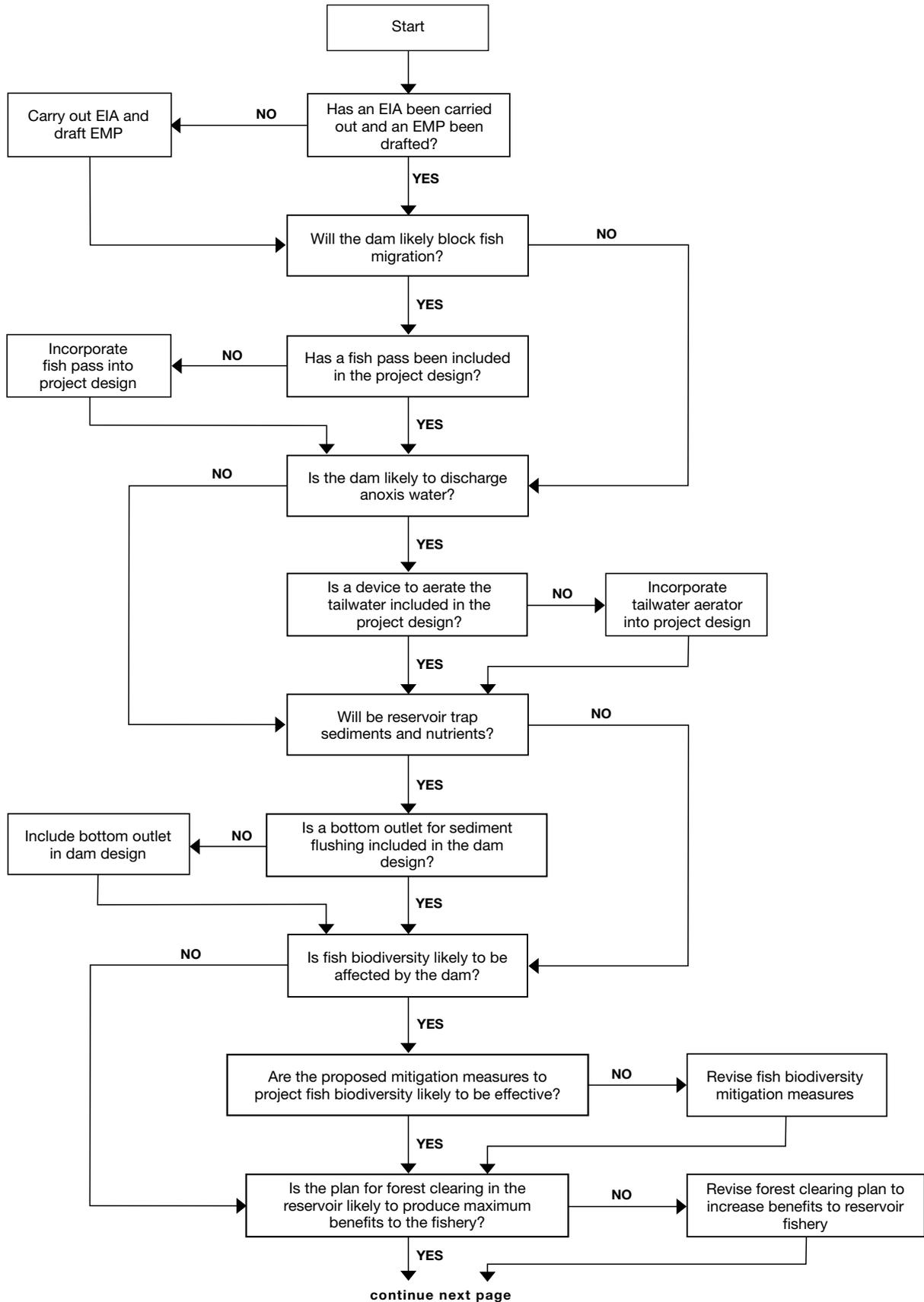
6.2 Fisheries Information Base Requirements

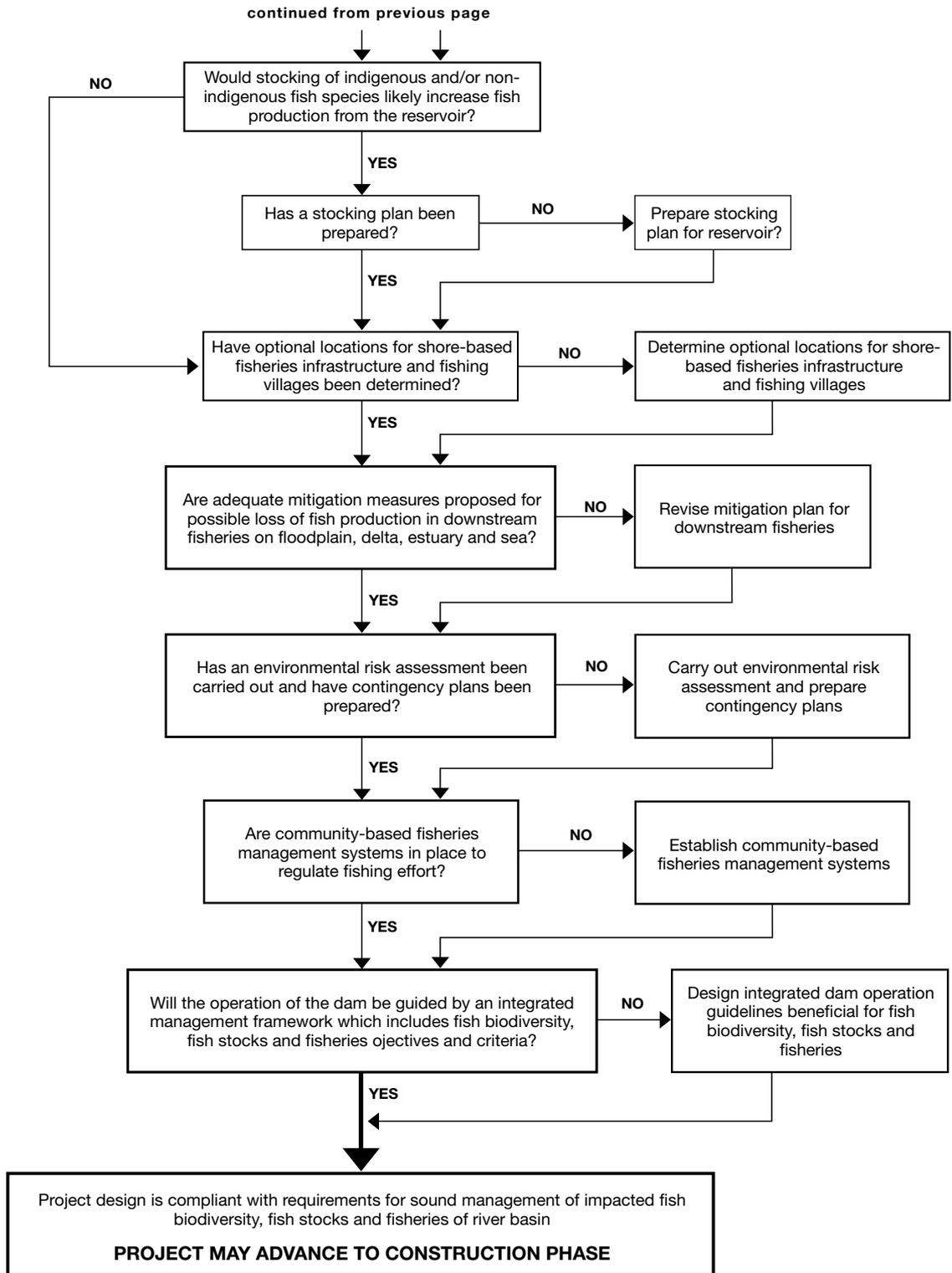
Appraisal is a process of examination and evaluation of a proposed project. The purpose is to determine the anticipated adequacy, worth and acceptability of the dam. At the end of the process, a recommendation would be given on whether or not to finance the project and proceed with construction. Project appraisal is carried out by the funding agency in association with other relevant authorities. The methodology is usually economic and financial in nature, but due consideration is also given to environmental factors and concerns. In recent years, fisheries concerns have been given high profile in some major dam projects (for example, Nam Theun II in Lao PDR).

During the appraisal phase, fisheries data presented in the EIA is reviewed. It is imperative therefore that all data and analytic outputs be presented in a form which provides concise defensible responses to the following questions:

1. What is the impact area of the dam with regard to fisheries (i.e. how far upstream and downstream)?
2. Will the dam result in the loss of fish biodiversity in the impact area? Which species and why?
3. Will the dam result in losses and/or gains in fish production in the impact area? Which species and why?
4. What will be the magnitude of impact on employment and income in upstream and downstream fisheries affected by the dam?
5. What are the feasible mitigation measures to fish biodiversity loss and fish production loss that the dam will cause? How effective will they be? What will they cost?
6. What impacts cannot be mitigated and will remain residual? How important are these impacts?
7. What risks to fisheries will the project present, and what contingency plans are to be adopted?
8. What is the overall assessment of the proposed dam with regard to fisheries? Based on the impact of the dam on fisheries should the dam be built or not built? Are there other project alternatives which are more attractive from the fisheries perspective?

A decision tree is shown in Figure 1 which presents a methodical and logical approach to evaluating a proposed dam project from a fisheries perspective. Various specialists are required to discuss the results of the EIA with the appraisal team, including a fisheries biologist, ichthyologist, fisheries engineer, and fisheries economist.





Note: Successful responses to all boxed item would result in project approval. A negative response to any one item would not allow progress to the next item until a successful solution is put forward. Failure to do so would create an impass which could be solved by considering other project designed or alternative projects.

Figure 1. A decision tree for use in evaluating a proposed dam project from a fisheries perspective during the project appraisal phase.

7. DAM CONSTRUCTION PHASE

7.1 Fisheries Management Capacity Requirements

Dam construction entails a relatively severe (but of lesser duration than the dam operation phase) and geographically limited interference with the riverine environment. The four main environmental threats to fisheries noted above in Section 2 each require specific fisheries management measures:

Soil erosion and silt runoff into the river: Proper construction practices and diligent attention to the control of erosion near the river banks during the removal of trees and soil cover will minimize problems of turbidity in the river and threats to fish stocks. Rainfall on the construction site will however still result in some fines (mostly clay) finding their way into the river. The washload should be carefully monitored upstream and downstream of the construction site(s) and preventive steps taken before mortality or undue stress occur among downstream fish stocks.

Siltation of key fish breeding, nursery or overwintering habitats in the river: Excessive bedload originating from the construction site should not be allowed to materialise. This can be controlled by proper construction practices. Key downstream fish habitats should be monitored to determine if a problem with sedimentation is developing.

Use of explosives: Damage to fish stocks from blast shocks can be controlled by preventing fish from gaining access to the blast area (i.e. erecting temporary fencing or screens in the river) and timing the use of explosives to periods when fish might less likely be in the area (i.e. daylight hours, dry season).

Blocking of fish migration: If feasible, the hydraulic characteristics of the diversion tunnel should be designed to be as fish friendly as possible. For certain types of projects, consideration should also be given to installation of a fishpass, either a temporary or a permanent structure.

Fisheries management during dam construction is essentially an exercise in local damage control. This is best carried out by a specialist fisheries team working under the project office. The fisheries team should have access to construction site managers and supervisors, funds for field work and construction activity, and authority to implement protective measures. The team should also involve the local fishing communities and fisheries management authorities in monitoring the impacts of construction on fish stocks and downstream fishery environments. The team should review all planned construction activities and schedules prior to commencement and suggest any improvements that could help to avoid detrimental impacts or might be beneficial to fisheries.

A special item of importance to fisheries during this phase is reservoir preparation. The clearing or non-clearing of trees and bush from reservoirs can have important consequences for fish production. Drowned trees provide a large surface area for periphyton and zoobenthos growth and thus substantially increase the food supply for fish (Ploskey, 1985; Bernacsek, 1984b). However, the trees also readily entangle fishing gears, thus decreasing the catchability of fish. Moreover, snagged nets can continue 'ghost fishing' for a considerable period. Besides entangling fishing nets, trees also readily anchor mats of nuisance floating aquatic macrophytes, which then continue expanding in area and can attain very large size. Without such anchoring, small macrophyte mats would normally be driven against the shoreline by onshore winds and most will become beached and die during water level drawdown. Drowned trees near the shore can be the worst culprits as they can anchor macrophyte mats over the highly productive shallow water littoral zone.

Partial clearing is the favoured approach to bush clearing. This allows cleared areas to be used for fish harvesting, and uncleared areas as foraging and shelter for fish. Moreover the anchoring effect for floating aquatic macrophytes must also be taken into account. Brush clearing (of whatever clearing pattern selected) is generally carried out during dam construction, although in some reservoirs clearing

has been done after dam closure (for valuable rosewood by divers using underwater power saws in Lao PDR and Thailand [Bernacsek, 1997b]) or for firewood in Ghana [Petr, pers.comm.]). The fisheries team should closely monitor brush clearing works to ensure that they conform with the chosen clearing pattern.

7.2 Fisheries Information Base Requirements

Fisheries management activities are very ‘hands on’ in nature during dam construction. Responsiveness to construction schedules is very important and much of the information must be real time (daily, hourly) in nature if it is to be used effectively to guide and control activities on the ground. Accordingly, sampling, data analysis and formulation of recommendation must be rapid and accurate, and inputs provided to the construction teams in a timely manner.

General information relevant to fisheries management during dam construction will be contained in three key documents: 1) the final dam design document, 2) the fisheries annex to the EIA, and 3) the dam construction plan. Among other things the documents will specify: construction schedules; the exact location and magnitude of excavations for dam foundations; routing and excavation works for river bypass channel; design and location of diversion tunnels; temporary or permanent fishpasses, particle size composition of disturbed soils and sediments, and gross volumes to be excavated; locations of camps, buildings, borrow pits, quarries, spoil and disposal sites; the location of forested areas that will be cleared and measures to minimize erosion; and, blasting schedules.

Specific parameters that the fisheries team will need to monitor on a continuous or frequent basis include:

- Suspended solids (washload) in the river downstream from construction sites.
- Bedload sediment transported downstream and deposition rates in key fish habitats.
- Any type of fish mortality, e.g. mortality of fish due to blasting.
- Migration of fish through dam site area.
- Fish biodiversity in the dam site area.
- Forest and bush clearing in the reservoir basin (to ensure compliance with plans for conserving certain areas as standing timber for fish shelters).

Professional fisheries expertise required to collect data and implement fisheries management during dam construction include fisheries biology, limnology, and fisheries engineering. Experts should be posted full time at the dam construction site.

8. DAM OPERATION PHASE

8.1 Fisheries Management Capacity Requirements

Once a dam has been commissioned, fisheries management tasks fall into four main groups:

- Management of the fisheries of the reservoir and its affluent streams.
- Management of the fisheries in the downstream river channel and floodplain.
- Management of the fisheries of the delta, estuary and adjacent sea.
- Management of the fish passage facility(ies) at the dam site.

Each of these presents special management problems, with regard to environmental parameters, as well as fishing effort regulation.

Reservoirs can contain important fisheries, and require comprehensive management in order to achieve sustainability. In developing countries, fishing villages sometimes proliferate rapidly after dam closure, attracted by the temporary boom in fish production caused by the trophic upsurge. The fishing effort can be excessive for post-boom stock production levels. The task of regulating fishing effort can therefore become fairly important early on in the life of a reservoir. The favoured approach is to implement fisheries management systems which are community-based, and involve individual fishermen and fisherwomen in managing the resource. There are several management support roles for government agencies including stock assessment research, training and extension, and overall regulation of the sector.

Some important fish species present in the reservoir migrate into the affluent inflow areas to spawn. There is a special need to protect these spawning grounds as fish here become densely concentrated and are especially vulnerable to fishing gears. Protection of the spawning broodstock is perhaps the single most important fisheries management task that needs to be carried out in reservoirs. At Ubolratana Reservoir in Thailand, a substantial increase in fish production was recorded after affluent stream inflow areas came under management protection during the spawning season (Bernacsek, 1997a). In contrast, intensive gillnetting in the single affluent river of nearby Sirinthon Reservoir resulted in severe reduction of the stocks of table fish (Bernacsek, 1997b). Generally, reservoir fish stocks benefit most from a closed season during the spawning migration into affluent streams. Brush should be cleared from inflow areas to minimize ghost fishing by snagged nets that have been illegally set. Enforcement of the closed season should be carried out by local fishing communities with the support of the government fisheries agency.

There are several successful approaches for enhancing and intensifying reservoir fisheries production (de Silva, 1988b; Bhukaswan, 1980; Petr, 1994, 1998). Stocking is perhaps the most widespread fisheries management practice in reservoirs. Stocking of reservoirs with indigenous and non-indigenous fish species is done for various purposes, such as to rehabilitate decimated stocks, to increase yields to fisheries and to control weeds. There are many examples of successful stocking and introductions of trout in cool reservoirs and tilapia and common carp in warmer reservoirs (see examples in Baluyut, 1983; Indo-Pacific Fishery Commission, 1988, 1991; de Silva, 1988a; Caldwell, 1983; Karpova *et al.*, 1996; Sugunan, 1995). Introduction of pelagic species such as the sardine *kapenta* in Kariba and Cahora Bassa Reservoirs in southern Africa have also led to productive fisheries (Marshall, 1984b; Bernacsek and Lopes, 1984a). Stocking is particularly important for the comprehensive reservoir fisheries management practices carried out in China (Sifa and Senlin, 1995; Lu, 1992; various papers in de Silva, 1992). Some non-indigenous species (i.e. Chinese and Indian carps) are unable to breed in reservoirs for various reasons, and must be re-stocked every year in order to appear as consistent components of the catch. Although re-stocking is expensive, the yield to the fishery can be substantial - especially in smaller reservoirs. Small dams have attracted fisheries management interest world-wide because they are very numerous and can give extremely high yields per unit area (van der Knaap, 1994; Giasson and Gaudet, 1989; Bernacsek, 1986, 1997a; Marshall and Maes, 1994; Moehl and Davies, 1993; Anon., 1995b). A precautionary approach should be followed when assessing potential introductions (FAO, 1996a).

The importance for reservoir fisheries of partial brush clearing of the reservoir basin prior to dam closure was noted in Section 7.1 above. In reservoirs of dams built in desert areas, there may be little or no drowned bush, and brush parks (i.e. fish attracting devices, FADs) can be installed to increase fish production. FADs can be in the form of branches fixed to the substrate and/or floating mats of aquatic plants.

Problems of ghost fishing by nets snagged in drowned trees may be mitigated by appropriate net design (i.e. short net lengths, elimination of foot lines, and use of thin low breaking strain twine) to make it easier to haul up an entangled net. Better net setting practices (i.e. setting along the tree stand margin rather than inside the stand) would also help. Not all such mitigation measures may be workable or effective in certain situations, and results should be carefully monitored and evaluated to determine a set of best practices to be normalized in a reservoir.

The problem of excessive floating aquatic macrophyte infestation can be controlled by a combination of flushing of nutrients out of the dam, occasional large drawdowns and biocontrol with plant eating fish such as grass carp. This will exert control over macrophyte outbreaks in the long term. In reservoirs where macrophyte infestations are more persistent due to heavy nutrient loading with agrochemicals from the watershed or municipal sewage, control may be achieved by spraying herbicides. Only environmentally friendly herbicides should be used in order to avoid lethal and sublethal toxicity effects on fish. A rapid kill-off of a large quantity of macrophytes may however lead to a temporary problem of water quality deterioration due to the rotting mass of plants. For small patches of macrophytes, mechanical removal can be used but this is relatively expensive.

Cage culture is a very productive form of aquaculture practised in the reservoirs of Vietnam, China, Indonesia, Philippines and elsewhere (de Silva, 1988b, 1992). Ultra high yields are often realized. However cage culture can also generate serious problems of water pollution.

In developed countries, reservoirs are routinely used for sport fishing and angling which target a small number of highly regarded species (especially trout, salmon, walleye, bass, pike, catfish and perch). Water level manipulation can have strong impacts on fish populations (productivity and behaviour) and can increase or decrease catchability. Fishing effort on temperate reservoirs can become intense, and natural recruitment (if it occurs at all) is often augmented with stocking. Although there are exceptions, fisheries management has generally focused on size restrictions and closed seasons, rather than limiting access. Recreational fisheries are however high value fisheries (due to the relatively high total expenditure per fish caught) and maintaining expenditures for stocking to support recruitment may not be a critical issue. Hence, there may be little incentive to protect spawning grounds in affluent streams and natural recruitment to the reservoir stock. A more urgent issue may be to maintain an adequate food supply (forage fish, aquatic insects and other macro invertebrates) for stocked species. Correct management of water levels to suit life cycle requirements of forage fish and invertebrate species, and provision of adequate woody substrates (drowned forest, brush parks) as invertebrate habitat are important management concerns.

Fishing may be prohibited in drinking water supply reservoirs. Biomanipulation of the reservoir biota through introduction of non-indigenous species or stocking of indigenous species is used in some countries such as Czech Republic to maintain a very high water quality standard.

A special hazard in reservoirs with large areas of gently sloping littoral substrate is contamination of reservoir fish with pesticides used in drawdown agriculture. Fisheries managers will need a mechanism by which control can be exerted over the type of pesticides used and the application methods and rates.

Management of fishing effort in downstream fisheries in the river channel and on the floodplain should follow community-based management protocols, with appropriate support from fisheries agencies. Because many dams will dramatically alter hydrological conditions and water quality parameters, special attention should be paid to minimising any negative impacts. The following impacts require implementation of effective mitigation measures:

- First filling of a reservoir: This can severely reduce stream flow and depress fish stocks. First filling of Ataturk Reservoir in Turkey severely reduced the discharge of the Euphrates River in Iraq which supplies the Mesopotamian Marshes (Maltby, 1994). Minimum stream flow guidelines should be followed, and the release of correctly timed mini-floods should be considered.
- Discharge of cool and/or anoxic water from the hypolimnion: This can drive fish downstream or even cause fish kills. Changes in fish abundance in the river below dams - due to oxygen depletion and altered discharge - have been recorded world-wide (Welcomme, 1985; Bernacsek, 1984a). Positioning of discharge structures at the highest possible elevation in the dam wall, improved turbine design and artificial aeration of discharge water would help to minimize this problem (March *et al.*, 1992; Anon., 1998).

- High turbulence in the stilling pool immediately below the dam: This can kill migrating fish by mechanical damage or nitrogen supersaturation, as well as block migration. Appropriate design of discharge structures to minimize turbulence and eliminate hydraulic jumps is needed (ICOLD, 1987; Clay, 1995).
- Blocking of fish migration: Dams usually block upstream fish migration and interfere with downstream fish migration. A variety of mitigation measures have been used to deal with these problems, and research is continuing to improve them further (Odeh, 1999). Fishpasses of one sort or another have been effective at many dams (Larinier *et al.*, 1994; Clay, 1995).
- Reduction of inundation of floodplains: This usually results in a large decline in fish catch from the floodplain, and can also impact fish biodiversity. Mitigation measures include conservation of remaining fish stocks on the floodplain by establishment of fish sanctuaries. Controlled limited flooding during the rainy season, and rice-fish culture during the dry season would help to keep floodplain fish production at a significant level.

Even if effective mitigation measures are implemented for the above impacts, fish biodiversity may still suffer due to the alterations in annual hydrological discharge pattern. Additional measures such as captive breeding and special sanctuary habitats may need to be introduced to assist endangered species.

Fisheries of downstream estuaries, deltas and adjacent seas generally suffer from alterations in river hydrology and sediment/nutrient trapping in the reservoir. Stocks of some commercially valuable marine species may become reduced. Decreases in pelagic fishes off the mouth of the Nile are attributed to the High Aswan Dam (Welcomme, 1985; Bernacsek, 1984a), and reduced estuarine prawns and shrimp stocks off the mouth of the Zambezi River are linked to Cahora Bassa Dam (Gammelsrod, 1992; Hogueane, undated; Bernacsek and Lopes, 1984b). Fisheries managers would need to anticipate such changes occurring and assist fishing fleets to scale back fishing effort to compensate. Options to minimize changes in hydrological discharge should be explored. For some types of dams it may be possible to conduct sediments through the reservoir and dam using gates set into the base of the dam. Mangrove forests in the delta may be negatively affected through erosion, and measures may need to be taken to stabilize shorelines and replant with saplings.

Some successes have been recorded in mitigating downstream impacts on fisheries. The Tennessee Valley Authority (TVA) was able to improve downstream dissolved oxygen levels through better timing of discharges and improved turbine design. Fishpasses have been built at many dams that have been successful in allowing migrating stocks of various species to surmount the dam wall. The correct choice of fishpass design is a critical factor (e.g. Larinier *et al.*, 1994). The experience in Australia is particularly instructive. Early fish ladders built in Australia were of the pool and weir design used for salmonids in the northern hemisphere. These proved to be unsuccessful for the slow swimming species present in Australian inland waters (Harris and Mallen-Cooper, 1993). In recent years, pool and weir ladders have been replaced by vertical slot fishpasses. These are very successful and allow large numbers of migrating broodstock and juveniles access to upstream habitats (Mallen-Cooper, 1994).

The operation and management of fishpasses entails a number of activities. Monitoring of fish traffic inside the fishpass during the main migration periods is crucial. At the minimum, the number of species traversing the fishpass, the number of individuals of each species and the length/weight ranges of each species should be determined. This information should be compared with data on fish movements immediately downstream of the dam, and upstream in the reservoir, in order to assess the efficiency of the fishpass in providing an access route for individual species. To determine the overall impact of the fishpass on reservoir fisheries and downstream river fisheries, routine monitoring data on fish biodiversity and fish production collected in the reservoir and in the downstream river channel should be compared to baseline data from before dam construction, and differences interpreted in the light of fishpass traffic monitoring data. If certain fish species are found to be incapable of using the fishpass and their productivity declines, a re-evaluation of the fishpass design will need to be carried out and adjustments made to the structure.

Hydrological conditions in impounded rivers can vary erratically. The social demands for the outputs of the dam (electricity, water) impose additional environmental stress over and above what may occur due to natural environmental variation from year to year. Output demands can vary in the short term and the long term. The needs of the fisheries sector with regard to management of the water mass (and water level) in a reservoir may be different from that required for hydroelectricity generation or irrigation water releases. There is a need to ensure that the fisheries sector is represented on the management board of the dam, and that fisheries criteria are incorporated into the design rule curves which guide dam operation. Without such representation, reservoir fisheries and downstream fisheries may suffer. For example, water management of multipurpose dams in Thailand is responsive to the needs for irrigation water, hydroelectricity production, domestic and industrial water supply, salinity control and navigation (Siriwadh and Sawatdirurk, 1989). Several operation rule curves are used (flood control rule curve, conservation rule curve, buffer rule curve, inactive rule curve). However, the water needs of the fishery sector are not included in any rule curve, despite its importance for food production. In contrast, the river modelling system for dams of the TVA include an application for tailwater aeration effects on fish growth. Reservoir water management should be based on an integrated approach. The impact area of the dam could be divided into integrated management units, and water management rules could be sensitive to the needs of each units.

Maintenance of adequate flows in downstream river channels (through managed water releases from the reservoir) is crucial for providing a viable aquatic environment for river fish. This is especially important where attempts are being made to restore previously decimated stocks of locally extinct species or threatened species. The prospect for rehabilitating populations of long distance migrating species such as salmon and sturgeon in impounded rivers in developed countries is very heavily dependant on providing an adequate flow regime in the river downstream of the dam. This will require the release of mini-floods which mimic the pre-existing natural flooding regime, and strict maintenance of adequate dry season flows. The duration of the flood release must be long enough to allow the stocks to migrate over the full distance of the migration route.

8.2 Fisheries Information Base Requirements

Two types of fisheries data are required during the Dam Operation Phase: 1) conventional data on catch and effort useful for regulating fishing effort to ensure sustainability of production, and 2) various data on fish biodiversity, fish stocks and environmental parameters that will allow monitoring of the efficiency of the environmental mitigation measures for fish biodiversity and fisheries being implemented. A portion of this data needs to be in real time or near real time format in order to allow rapid corrective management responses to unforeseen impacts (contingencies).

In general, there should be comprehensive monitoring of dam impacts on fish biodiversity and fish production upstream (reservoir, affluent inflow streams) and downstream (river, estuary, delta, sea). The focus should be on water quality, fish migration behaviour and the numbers of fish per species actually passing the dam, fish biodiversity inventory, fishing activity, the effect of water level drawdown and impounding in the reservoir, and the effect of dam discharges on downstream aquatic environments. Special focus needs to be put on: ghost fishing by nets snagged in submerged trees in the reservoir; migration of reservoir broodstock to affluent inflow areas to spawn; congregation of fish below the dam attempting to migrate upstream; and, the loss of fish production on the floodplain (ie migrant and resident species), in the estuary and delta (ie prawns and shrimp) and in the sea (small pelagics) due to changes in volumes and seasonality of freshwater discharge and/or nutrient rich sediment.

Impact monitoring will generate a large, ever expanding fisheries and environment data base which will require timely analysis and information management if it is to be useful for managing fish biodiversity and fisheries. Particularly important is the construction and maintenance of a dynamic model of the fisheries upstream and downstream of the dam. The model should be based on various environmental parameters (especially hydrology), and demonstrate how variations in environmental parameters result in changes in the fisheries conditions and outputs. The TVA has several models for river hydrology and

environmental impacts, including the effect of dissolved oxygen on fish growth. This helps to guide operation of its cascade of dams in a manner which reduces stress on fish stocks.

9. DAM DECOMMISSIONING PHASE

9.1 Fisheries Management Capacity Requirements

Decommissioning and demolition of a dam has the potential to restore a river to near pre-dam hydrological conditions. Ideally, migrating fish would again have unrestricted access to the upstream tributaries (see Anon., 1999, for the example of the recently decommissioned Edwards Dam in the USA). The productivity of downstream floodplain fisheries may be restored, and sediments and nutrients would again reach the delta, estuary and sea. In theory, the impacts of a dam are reversible. In practice however, dam decommissioning may result in only a partial environmental recovery. Certain fish species may have been lost forever, while changes to the environment (clearing of the reservoir basin upstream and the floodplain downstream) may be difficult to reverse or prove to be irreversible.

Fisheries management faces three challenges during dam decommissioning: 1) prevent damage to fish stocks during dam demolition, 2) assist rapid recovery of affected fish biodiversity and fish stocks, and 3) implement effective environmental enhancement measures to achieve recovery of the aquatic and related terrestrial environments. Environmental threats during dam demolition are analogous to those that can occur during dam construction and should be mitigated in a similar manner (see Section 7.1 above). Care should be exercised to prevent migrating fish stocks from entering into an area where blast damage or sediment toxicity could occur before demolition is completed.

Fish stock and habitat restoration will likely take several years (or possibly decades) to achieve. Apart from restoration of the dam site, major tasks above the dam site are management of sediment formations deposited by affluent streams in the upper part of the reservoir and restoration of river bank forest cover and other plants. Below the dam site, some work may be required to restore the bank ecology of the river channel, and the forest cover on the floodplain and delta. Stocking to rehabilitate faltering fish biodiversity and fish stocks should be considered, especially species which suffered most during the dam operation phase. Special measures to regulate catch and effort for fish species undergoing recovery programmes would be needed. Fisheries management systems should have general continuity with those of the Dam Operation Phase. Emphasis should shift downstream to the floodplain and saltwater environments as the reservoir fishery would no longer exist.

9.2 Fisheries Information Base Requirements

Information needs during dam decommissioning are less voluminous than during dam operation. Fish biodiversity and fish migrations should be carefully monitored to determine the effectiveness of recovery programmes. Sediment transport (washload and bedload) should also be monitored. General catch and effort data should continue to be collected to meet the needs of fishing effort regulation.

10. REGIONAL CHARACTERISTICS OF VARIOUS DAM TYPES

The main dam types are: hydroelectric dams, flood control dams, irrigation dams, domestic and industrial water supply dams, recreation dams, fish breeding dams, and navigation dams (Lecornu, 1998). Dams can also be grouped into single purpose dams and multipurpose dams. It may be supposed that environmental mitigation of a single purpose dam might be easier than for a multipurpose dam simply because there are fewer factors to consider, but this is not necessarily the case.

On balance, hydroelectric dams have the most severe environmental impacts because of their great height. This creates a massive hydraulic jump across the dam which is usually insurmountable by migrating fish. Irrigation dams also generate significant fishery impacts. They usually discharge only hypolimnion water (i.e. from the bottom of the dam wall), and there is also a persistent hydraulic jump which blocks fish migration. Flood control dams such as Jebel Aulia in Sudan store water only during the flood season, and then release it gradually during the dry season. At the end of the dry season and beginning of the rainy season there may be no hydraulic jump at the dam, and this allows fish to migrate freely through the dam for part of the year. Flood control dams may therefore be somewhat more fish friendly. Domestic and industrial water supply dams ideally have near stable water levels all year round and may discharge only epilimnion water. In some cases, the water authority does not permit fishing in the reservoir. Recreation dams typically cater for small recreational boats, windsurfing, swimming and angling, while fisheries dams are built specifically to breed and produce fish. Some large fisheries dams (ie Beung Boraphet in Thailand, Anon., 1982) are fitted with fishpasses to allow migrating broodstock to enter the reservoir. Navigation dams raise upstream river water levels to facilitate the movement of boats.

Multipurpose dams carry out several different functions. Water management is a complex undertaking as it must continually seek optimal compromises between the various - often conflicting - output demands. Few dams incorporate fisheries protection criteria into their operating rules because fisheries is not a priority for the dam operator. However, the successful experience of the TVA in catering for downstream oxygen levels required by fish for a cascade of multipurpose dams suggests that such mitigation would be feasible elsewhere.

The dams and reservoirs of the world fall into two major groups in terms of fisheries management. In North America, Europe and Australia most reservoirs are used for sport fishing (Hall, 1971; Miranda and DeVries, 1996; Anon., 1967, 1996). They are stocked with species favoured by anglers (trouts, salmon, basses, catfish, carp, perches, pikes). In Asia, Africa and South America, most reservoirs are used for artisanal and commercial food fish production. These fisheries are based on indigenous stocks and introduced species (either self-sustaining or periodically restocked populations) such as tilapia, carps, characids, and catfishes. Other differences between regions are related to latitude (i.e. ice cover in winter), rainfall patterns, and the composition of the indigenous fish biodiversity.

An important difference between developed and developing countries lies in the degree of mitigation of environmental impacts on the downstream river stocks. The former generally spend more on improving oxygen levels in tailwaters, installing fishpasses, and maintaining adequate flows to protect downstream aquatic ecology. In most developing countries, there is little or no mitigation of downstream impacts. Developed countries also have relatively much larger information bases to work with, and develop superior technology to solve fisheries problems. Dam operators in developing countries often have to rely on far less precise or sophisticated procedures and equipment, as well as poor data bases.

11. LEGAL ASPECTS OF MANAGEMENT OF FISHERIES AFFECTED BY DAMS

In most countries, general rules and authorities for fisheries management are contained in national and provincial/state fisheries legislation (typically a "Fish Act"). Specific rules are proclaimed in periodically revised regulations (ie size limits and closed seasons). Legislation which deals with water management and regulation of rivers is usually contained in water resources acts. There will often also exist an environmental act which defines general EIA requirements for development projects, and sometimes requirements for specific project types such as dams. Other environmental legislation may exist which focuses on protecting biodiversity, regulating introduced species, controlling pesticides, establishing protected areas, and managing forests.

Clearly all these types of fisheries, water resources and environmental legislation are of relevance to fisheries management in impounded river basins. It would be an extremely important exercise for the national fisheries agency of a country to carry out a comprehensive review of all existing legislation relevant to management of fisheries affected by dams. The objective of such a review would be three fold:

1. To produce a comprehensive collation and synthesis of existing legislation.
2. To identify gaps in existing legislation which could render fisheries vulnerable or endangered.
3. To draft new legislation which fill gaps or otherwise upgrade and enhance existing legislation.

There are a number of specific technical concerns which the review should examine, including:

- Are the legal requirements for EIA of dam projects (large or small) of the country and the financing agency adequate to accurately and comprehensively identify location-specific impacts and mitigation measures?
- Is fish biodiversity both upstream and downstream adequately protected by legislation?
- Are the legal requirements for water quality and discharge in the river channel downstream of the dam adequate to protect fish stocks and aquatic ecology?
- Does legislation exist which requires that dams be fitted with fishpasses or some other type of bypass mechanism (both for upstream *and* downstream passage), and do there exist legal provisions that require improvement to be made to existing fishpasses if they are found to be insufficiently effective?
- Are the criteria for selecting non-indigenous species for stocking in reservoirs stringent enough to protect indigenous fish biodiversity?

Apart from determining if existing laws and regulations are adequate, and what new legal instruments are needed, the review should carefully consider the procedural problems associated with amending laws. Solutions should be found which will facilitate installation and improvement of mitigation measures and allow ready modification of management measures, processes and constructions to optimize conditions for fish biodiversity and fisheries. One approach could be to legally embody the possibility for modification of dam operation conditions in relation to fish biodiversity and fisheries at the time of renewal of the dam concession. The EMP should be a legally binding contract which obliges the dam proponent to carry out specified environmental mitigation activities. The proponent could also be legally bound to spend a certain fraction of revenue from the dam on fisheries research and mitigation. The dam owner could be legally obliged to implement certain desirable mitigation measures once they have been identified as the appropriate solution to a particular impact problem. The work carried out under the EMP should be reviewed periodically (ie annually) by an independent body of fisheries specialists, who would assist the dam owners to draft updated workplans.

A special approach to protecting fish and aquatic biodiversity that might be considered for formal adoption in national environmental legislation is the criterion that *'no loss of biodiversity should take place as the result of dam construction and operation'*. Clearly such a legal requirement would be extremely rigorous, and undoubtedly few dam projects would be able to meet the criterion in the present day. It may therefore not be realistic to advance this criterion as a feasible rule in the medium term future. *Nonetheless, this is the goal that all dam projects should strive for.* It may be possible to specify quantitative limits to acceptable loss in biodiversity. This would allow an assessment to be made of how closely the dam project approaches the 'no biodiversity loss' criterion. These quantitative limits could over time be made more restrictive, thus forcing dam proponents to improve mitigation technologies.

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