Contributing Paper

Capacity and Information base Requirements for Effective Management of Fish Biodiversity, Fish Stocks and Fisheries Threatened or Affected by Dams During the Project Cycle.

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Dams, ecosystem functions and environmental restoration

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Contents

Executive Summary

1. 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.
2. 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.
3. 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.
4. 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.
5. 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.
6. 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).
7. 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.
8. 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.
9. 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.
10. 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.

11. 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.
12. 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.
13. 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.
14. 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 is crucial to maintaining a suitable environment for migratory fish species, especially endangered species.
15. 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.
16. 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.
17. 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.
18. 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.
19. 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.

20. 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 centralised 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 realised, 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 (ie 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 world-wide. 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 specialised 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 & Conelly (1985), Ruddle (1987), Asada et al (1983) and Berkes & 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 (ie 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 (ie 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 characterised 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 optimise 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 (ie 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 economise 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 situation.

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 optimised, 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 (ie 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.

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 minimise 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 (ie 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 (ie 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.com.]). 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 minimise 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 minimise 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;

Caldwellader, 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 & Lopes, 1984a). Stocking is particularly important for the comprehensive reservoir fisheries management practices carried out in China (Sifa & Senlin, 1995; Lu, 1992; various papers in de Silva, 1992). Some non-indigenous species (ie 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 & Gaudet, 1989; Bernacsek, 1986, 1997a; Marshall & Maes, 1994; Moehl & 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 (ie 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 realised. 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 minimise 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 minimise 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; Hoguane, undated; Bernacsek & Lopes, 1984b). Fisheries managers would need to anticipate such changes occurring and assist fishing fleets to scale back fishing effort to compensate. Options to minimise 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 stabilise 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 & 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 & 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 (ie 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 & 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 (ie 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 optimise 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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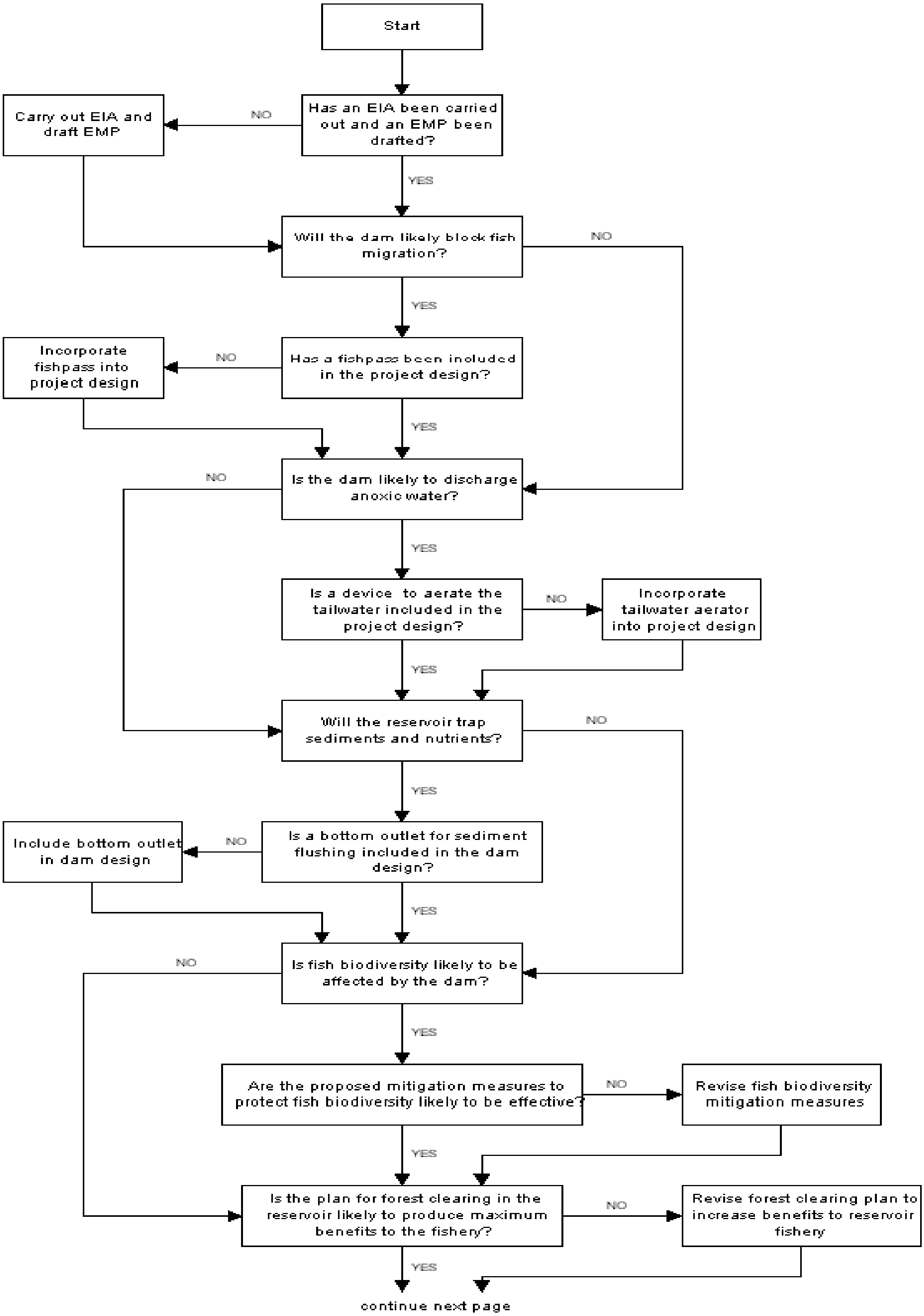
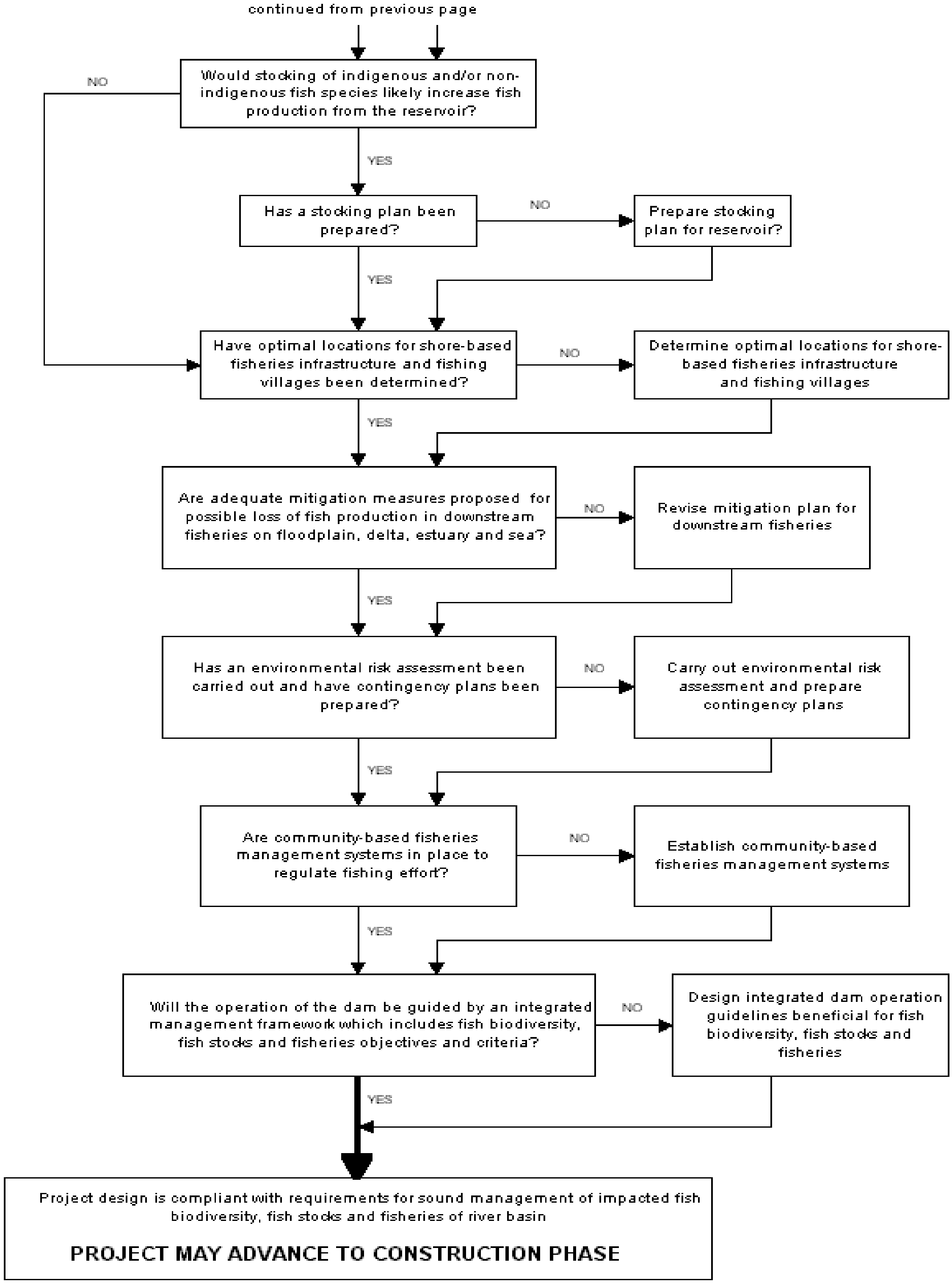

Start
Has an EIA been carried out and an EMP been drafted?
NO
Carry out EIA and draft EMP
YES
Will the dam likely block fish migration?
NO
YES
Has a fishpass been included in the project design?
NO
Incorporate fishpass into project design
YES
Is the dam likely to discharge anoxic water?
NO
YES
Is a device to aerate the tailwater included in the project design?
NO
Incorporate tailwater aerator into project design
YES
Will the reservoir trap sediments and nutrients?
NO
YES
Is a bottom outlet for sediment flushing included in the dam design?
NO
Include bottom outlet in dam design
YES
Is fish biodiversity likely to be affected by the dam?
NO
YES
Are the proposed mitigation measures to protect fish biodiversity likely to be effective?
NO
Revise fish biodiversity mitigation measures
YES
Is the plan for forest clearing in the reservoir likely to produce maximum benefits to the fishery?
NO
Revise forest clearing plan to increase benefits to reservoir fishery
YES
continue next page



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 designs or alternative projects.

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