1. INTRODUCTION

1.1 Context

Inland waters provide a wide range of services for human communities as well as being a basic element in the development of agriculture, transport, industry and power generation. Such ecosystem services include fundamental ecosystem services, such as those required to support a healthy ecosystem and fish, and demand-derived services, such as fish production for fisheries (Holmlund and Hammer, 1999). Human influences on rivers, lakes and estuaries usually result in changes to the form and function of inland aquatic systems with an associated decline in the ecosystem services that they can offer.

The rate at which the form and function of inland waters are being modified is increasing as populations expand and their economic development grows. A global overview of dam-based impacts on large river systems carried out by Nilsson *et al.* (2005) shows that over half are negatively affected by dams. If the types of impact are extended to include other forms of modification, such as channelization and floodplain reclamation, the percentage of modified systems would be considerably higher.

FAO Members have a responsibility to maintain aquatic ecosystems in a state consistent with the sustainability of fish stocks and the fisheries they support. Article 6.1 of the General Principles of the Code of Conduct for Responsible Fisheries requires that “States and users of living aquatic resources should conserve aquatic ecosystems. The right to fish carries with it the obligation to do so in a responsible manner so as to ensure effective conservation and management of the living aquatic resources.”

Initial efforts to improve ecosystems for fish and fisheries date to the latter part of the nineteenth and early twentieth centuries when modifications were made to rivers and streams to promote salmon populations. At the same time simple pool type fishpasses were invented so that migrating fish could pass weirs and other obstructions. Despite the development of such methods, much more attention was being paid through the first half of the twentieth century to water quality issues as the large scale pollution of many rivers, lakes and estuaries in North America and Europe led to them becoming virtually fishless. The extended programme of dam building that occurred on all continents during the second half of the twentieth century has led to much more attention being paid to the development and construction of fishpasses adapted to species other than salmon. It also led to considerable research into the management and exploitation of the fish populations that developed in the newly created reservoirs.

More recently, the growing awareness of the general degradation in the form and function of rivers caused by engineering and water abstractions is focussing attention on the need to improve these degraded habitats. These guidelines are based on the experiences with habitat improvement throughout the world. However, as the major efforts to restore and rehabilitate rivers and lakes have been confined mainly to river systems in Europe and North America that are not particularly big on a global scale, many of the techniques proposed for larger rivers, lakes and seasonal wetlands are still in their early stages of development. Equally, the transfer of these approaches to the tropics is still exploratory and needs to be developed in the growing understanding of how such systems function.

The following guidelines were prepared to cover the policy and economic framework for decisions regarding rehabilitation of inland waters and estuaries. They also outline major technical solutions to rehabilitation of migratory pathways and physical structure of the environment. They address different strategies, concepts and approaches, and social, economic and legal issues, simple approaches to assessment and evaluation of waterbody status and measures for improvement of water quality. The guidelines discuss general technical measures for managing vegetation in lakes and rivers, solutions to river structure and connectivity and measures for rehabilitation of lakes and reservoirs. Finally, the guidelines address measures for monitoring success or failure of rehabilitation measures.

1.2 Strategies

The term “improvement of inland water ecosystems for fish” is used to cover a range of strategies[1] that represent the various options open to aquatic resource managers. In some cases several strategies may be pursued in parallel. For example, rehabilitation may occur in river channels while long-term water quality issues are mitigated for by water treatment plants.

1.2.1 Protection

In the narrowest sense, protection means the conservation of an unspoiled site in its pristine condition. However, as these sites are quite rare (at least in heavily populated countries or areas), protection also pertains to the conservation of sites that are still in a (relatively) natural state, or at least close to this, but not necessarily pristine. Protection efforts should seek to discourage physical modifications such as the building of dams, levelling of river channels, draining of floodplains and wetlands and the revetting of lake shores within high quality environments. Environments are often protected as national parks, reserves, sites of special scientific or naturalistic interest, or designated areas of great natural beauty. Designation of such areas needs careful evaluation in view of the potential cost to local communities and it is often preferable to protect environments within a

[1] The terminology relating to these activities is extremely confused with the same term being used for a number of different approaches – see Glossary.

working landscape. However, costs should not be the reason for doing nothing.

1.2.2 Restoration

Restoration means to return an aquatic system or habitat to its original, undisturbed state and can often only be pursued in the context of larger scale landscape conservation as in national parks or wilderness regions. Current land use patterns or societal preferences determine the practicability of this solution. For example, it is extremely difficult, and probably undesirable, to return to the fully forested and swamp-like pristine condition in any but the smallest of basins in Europe. In other parts of the world, where there is less population pressure, a local return to the wilderness state may well be possible.

1.2.3 Rehabilitation

Rehabilitation is to restore functionality to a modified water course or waterbody where the pressures producing the modification have eased or ceased or where new technology can be introduced to reduce stresses. Rehabilitation often requires a single, sometimes major, expenditure. This is often followed by smaller-scale maintenance activities. Because the present state of the river or lake to be rehabilitated is the result of a series of modifications to the landscape, the true objective of rehabilitation is frequently poorly defined. Current land use patterns or societal preferences may well determine the result and efforts to rehabilitate are frequently thwarted by lack of knowledge of the pre-existing condition or of the requirements of the original fish communities.

1.2.4 Enhancement

Enhancement or intensification implies the modification of aquatic resource habitat or resource to increase productivity for fishery purposes. It is sometimes used to describe habitat rehabilitation or improvement, but often used to describe aquaculture activities. Enhancement can be at an extremely extensive level or may be intensified into forms of aquaculture. Such activities are usually coupled with other uses of the aquatic system and, in particular, with livestock rearing and agriculture. While enhancement can have positive effects on fish production, e.g. by impounding small streams to create chains of small dams or by constructing drain-in pond systems in wetlands benefiting one user or a (small) group of users, there might be negative effects to the open-access fishery on which depend other segments of the population. Also, modifications of the ecosystem for increased production may not be considered acceptable for biodiversity and conservation but are being increasingly used in systems that are modified for agriculture and human habitation. Therefore, a comprehensive assessment prior to enhancements is needed to establish social and environmental pros and cons.

1.2.5 Mitigation

Mitigation seeks to offset the impacts of an ongoing use of the aquatic resource that is judged to have a greater social and economic value than fisheries and the fish. Furthermore, in many cases historical changes to inland aquatic systems are effectively irreversible for ecological, social and economic reasons. In such circumstances managers should seek to make the best of the modified system by a series of interventions and management strategies designed to lessen the impact of stress. Such interventions tend to be local in scope aimed at solving individual problems. Actions include the creation of artificial habitat, arranging for flood simulating water releases or systematic stocking to maintain populations of fish that have no alternative source of recruitment. Mitigation usually involves recurring expenditures, which should be considered part of the cost of the major modifying use of the system.

1.2.6 Do nothing

Doing nothing is advocated where the state of degradation is such that there is no scope for an intervention in the near future (e.g. if there is a series of high dams without fishpasses *and* no spawning grounds upstream). It may also be considered where society places an extremely high value on sectors whose processes produce grave and lasting impacts on the living aquatic resources, although in such cases the degradation should not be allowed to progress to a point where the option of rehabilitating the system if the value of the impacting sector declines is no longer possible. Doing nothing is also advocated where the aquatic ecosystem is already functioning adequately within the priorities of society.

Guidelines – strategies

i) Every effort should be made to preserve inland waters that have not yet been strongly affected by development.

ii) It is better and less costly to protect existing high quality environments than to attempt to recuperate them once they are degraded.

iii) Costs of the mitigation of environmental impacts of any activity that modifies aquatic system form and function should be incorporated into the costing of the modifying activity at its inception.

iv) Managers should seek to rehabilitate damaged aquatic systems as fully as possible consistent with the social and economic conditions in the basin.

v) ***Restoration to an original condition should only be attempted in areas where human population pressures allow for a return to a pristine condition.***

vi) ***In systems where there is a need for increased production of food or other goods provided by the living aquatic resources over those that can be obtained naturally, the existing production system may have to be altered to favour such activities. In systems where this approach is advocated, enhancements should be done in such a way that any system diversity alterations or losses are mitigated. A comprehensive assessment should be carried out prior to the proposed changes.***

vii) ***In some systems the state of degradation might be such that there is no scope for rehabilitation in the near future. In such systems, where societies place an exceptional value on an economic activity that degrades the resource, attempts to recuperate the aquatic environment may be unproductive. Nevertheless, the degradation should not be allowed to progress to a point where the option of rehabilitating the system if the value of the impacting sector declines is no longer possible.***

1.3 Concepts and approaches

The various strategies can be applied at different spatial scales. These target different groups of organisms and have different social, economic and administrative implications. The approaches listed below are not necessarily mutually exclusive.

1.3.1 The basin approach

The basin approach seeks to protect, restore or rehabilitate the river or lake basin as a whole or to restore representative ecosystems within the basin and the connections between them. This is especially important for riverine migrant species that have different breeding, feeding and shelter habitats dispersed throughout the system, irrespective of the distance that lies between the different habitats, as well as for anadromous and catadromous species, where the connectivity from the sea to river headwaters is imperative. It is also very important in lakes and reservoirs where elements of the fauna migrate up inflowing rivers to breed. The basin approach assumes that r*ehabilitation* at basin scale will allow the whole natural fauna of the basin to restore itself.

Basin-scale projects are often very large scale and very costly. They may take place over a large geographical area that may involve more than one country or administrative district. Furthermore, because basin scale activities may involve interventions in land use patterns such as forestry or agriculture, and improvements in the connectivity of river channels, rehabilitation may rely on a number of administrative agencies. The basin approach does not imply complete restoration of the basin but rather key elements of it that are required for the sustainability of the maximum number of species in the basin's fish assemblage. It can, therefore, be tied to the "string of beads principle".

1.3.2 An ecosystem approach

The ecosystem approach attempts to restore the processes that create or maintain habitat. It approach assumes that the appropriate fauna will re-establish with the improvement of the ecosystem.

Ecosystem-scale projects may be local or of larger scale and may be incorporated into the basin approach when a number of ecosystems from different parts of the basin are treated together. An ecosystem approach may be associated with parks, reserves or sites of special scientific interest. Ecosystem-scale activities may also involve local interventions in land use patterns and may require cooperation between a number of administrative agencies.

1.3.3 The species approach

The species approach concentrates on one or more species judged to be of particular economic or social value (flagship species). Many of the improvement efforts carried out so far have been directed at economically important migratory species such as the salmons, which have very particular habitat requirements. The approach does not generally concern itself with species other than the target species but there is an underlying assumption that if the flagship species is doing well most other species present will also be in a good state. However, this has to be fully demonstrated and while this approach may work well in relatively species-poor temperate systems, it may not work satisfactorily in very species-rich tropical systems.

1.3.4 Scale

Rehabilitation can be carried out at a number of spatial scales depending on the target organisms or communities. The *habitat* scale is a highly limited area of a lake or river that corresponds to the needs of a particular static fish community or to certain life stages of a group of species. The *reach* in rivers or the *sector* in lakes groups a number of habitats into a functioning system for species or communities that depend to some extent on longitudinal movements. In some cases river reaches can be grouped into larger sectors consisting of several reaches or tributaries within the network. The *network* scale (sometimes called the watershed or basin scale) applies to the river or lake basin as a whole including tributaries (see Lowe *et al.*, 2006 or discussion of this issue applied to rivers). Examples of the application of scale are that some small species pass their whole lives in restricted habitats such as rocky riffles, whereas another species may use such habitats only for depositing their eggs. If the aim of rehabilitation is to conserve a species of limited range then action at the habitat scale may suffice. If rehabilitation is aimed at a wider ranging species the reach or network scale actions may be necessary. As the cost and complexity of any activities increase with increasing scale, it is of interest to limit the scale of the operations as far as is consistent with a good outcome.

Guidelines – concepts and approaches

i) ***Unless there are over-riding social and economic considerations, it is better to operate at the basin and ecosystem scales than the species level when restoring or rehabilitating complex fisheries assemblages.***

ii) ***Rehabilitation should be carried out at the spatial scale most appropriate to the needs of the target species or communities.***

iii) ***Ecosystem-scale rehabilitation should aim to restore the processes that maintain and create habitat***

2. SOCIAL, ECONOMIC AND LEGAL ISSUES

Inland waters and their resources have deep cultural, economic and social significance, and are governed by legislation and tradition in most of the world's cultures. This means that any modification to the aquatic ecosystem should be accompanied by adjustments to legal and regulatory frameworks that have to be taken into consideration when making proposals for activities that either degrade or improve the system (see Moss (2006) for information of these aspects in Europe).

2.1 Ecosystem services

Healthy ecosystems generate a number of services for humanity over and above the production of food through fisheries and gathering of aquatic vegetation (Table 1). These services contribute to the health of human populations and make a hidden economic contribution to the well being of societies. Damage to ecosystem structure and functioning can seriously diminish the capacity of the environment to sustain many of these services. Thus efforts to restore or rehabilitate aquatic environments should aim at the restoration or rehabilitation of ecosystem services as a whole.

Guidelines – ecosystem services

i) Rehabilitation or restoration of aquatic ecosystems for fisheries should also seek to restore or rehabilitate the whole range of ecosystem services.

2.2 Societal goals

2.2.1 Uses of aquatic environments

Inland waters are used by humanity for a great range of activities. Many of these require changes to the natural form and function of rivers and lakes or may produce such changes as a side effect. Table 2 summarizes some of these activities and the effects they can have on aquatic environments.

Fishing is one of a range of human activities in inland waters and forms part of a multi-use system. All uses should be guided by the precautionary approach. Activities that impact on the form and function of the aquatic ecosystem will affect all uses to a greater or lesser degree and should be carried out with a clear view as to the effects on other users and incorporate the "user-pays-principle". All projects to rehabilitate, restore or enhance aquatic habitats should be subject to thorough assessment of the ecological, social and economic implications and impacts.

Table 1. Major ecosystem services generated by freshwater ecosystems and fish populations (after Holmlund and Hammer, 1999).

<table>
<tr><th colspan="2">Fundamental ecosystem services</th></tr>
<tr><th>Regulating services</th><th>Linking services</th></tr>
<tr><td>• Regulation of food web dynamics
• Recycling of nutrients
• Regulation of ecosystem resilience
• Redistribution of bottom substrates
• Regulation of carbon fluxes from water to atmosphere
• Maintenance of sediment processes
• Maintenance of genetic, species, ecosystem
• Biodiversity
• Regulation of water quality – self purification</td><td>• Linkage within aquatic ecosystems
• Linkage between aquatic and terrestrial ecosystems
• Transport of nutrients, carbon and minerals
• Transport of energy
• Acting as ecological memory</td></tr>
<tr><th colspan="2">Demand-derived ecosystem services</th></tr>
<tr><th>Cultural services</th><th>Information services</th></tr>
<tr><td>• Production of food
• Aquaculture production
• Production of medicine
• Control of hazardous diseases
• Control of algae, macrophytes and other invasive organisms
• Reduction of waste
• Supply of aesthetic values
• Supply of tourism and recreational opportunities</td><td>• Assessment of ecosystem stress
• Assessment of ecosystem resilience
• Revealing evolutionary tracks
• Provision of historical information
• Provision of scientific and educational information</td></tr>
</table>

Table 2. The impacts of various human activities on the form and function of inland waters.

Use	Mechanism	Effect
Power generation	• Dams/weirs	• Creates new water bodies in the form of reservoirs • Interrupts longitudinal connectivity of rivers • Stops water flooding the floodplain in rivers • Dries out or alters wetland regimes • Changes water discharge patterns in rivers; hydropeaking • Changes water temperature patterns • Changes in oxygen content downstream • Increases drawdown in lakes and reservoirs • Changes to erosion-deposition regime in rivers • In estuaries may change salinity regimes • Replaces a lotic environment with a lacustrine one
Flood control	• Dams/weirs • Levees • Channelization	• As above • Interrupts lateral connectivity in rivers • Dries out or alters wetland regimes • Suppresses channel diversity
Navigation	• Dams, weirs and locks • Channel straightening and deepening – channelization • Removal of rapids, boulders or other navigation hazards • Removal of instream wood	• As above • Changes in the structure and functioning of river channels • Loses riparian and bottom habitat in channels • Suppresses multi-channel rivers in favour of single channels • Changes in basin morphology • Simplifies channel structure and loss of habitat diversity

Water abstractions or transfers for domestic consumption, agriculture and industry	• Dams/weirs • Removal of water from a donor system • Discharge of water into a recipient system	• See above • Changes hydrographs in donor and recipient basins • May dry out lakes, reservoirs and river channels • Introduces inappropriate drawdown regimes in reservoirs • May alter water chemistry and/or water quality
Domestic use	• Dams • Water transfers • Domestic sewage • Building on floodplains • Building on lake shores including marinas • Removal of riparian forests for firewood and charcoal	• As for dams • As for water transfers • Eutrophicates or pollutes lakes and rivers • See flood control • Reduces shoreline diversity • Reduces bank diversity, shade, structure and stability and increases erosion
Road building/bridge building	• Embankments • Culverts and bridges • Sills	• Interrupts connectivity • Increase sedimentation • Increased runoff • Reduce riparian diversity
Agriculture	• Dams • Water extraction • Diffuse fertilizers and animal wastes discharges • Pesticides discharges • Conversion of floodplains and wetlands to agriculture • Bad land use practice	• As for water transfers • Alters flow regimes • Eutrophicates rivers, lakes and estuaries • Pollutes rivers, lakes and estuaries • Loses floodplain and reduces lateral connectivity • Increases siltation of rivers, lakes and estuaries
Forestry	• Removal of vegetation cover	• Alters runoff patterns • Increases siltation of rivers and lakes: Changes erosion-deposition regimes in rivers

Livestock	• Access to riparian habitat • Defecation	• Destroys riparian habitat by trampling and grazing in rivers • Contributes to increased eutrophication/diseases
Wildlife conservation	• Set aside of areas as national parks and conservation areas	• Usually positive reinforcing fish populations but may conflict with fisheries needs or access
Industry	• Waste discharge • Water abstractions • Toxic spills	• Pollutes lakes and rivers: accumulation of toxic products in fish flesh and sediments • Contributes to altered hydrographs • Fish kills
Mining	• Waste discharge • Discharge of tailings • Gravel extraction from channel • Toxic spills	• Increases sedimentation and changes to erosion-deposition regimes • Produces long-term pollution of the water and sediments • Damages pool-riffle structures in upland rivers

Guidelines – use of aquatic environment

i) Proposals for habitat improvement in inland waters must conform to relevant legislation or traditions.

ii) Improvements to inland water ecosystems carried out for fisheries purposes should be consistent with other uses of the system according to societal goals.

iii) Conversely, where the major interest is thought to lie with restoration or rehabilitation, other uses may have to adapt to the altered state of the water course or water body.

iv) Projects for the improvement of aquatic habitats should only be carried out after a thorough impact assessment.

2.2.2 Land ownership

Most land throughout the world is owned and controlled by individuals, corporations or governments. This is especially true of valuable lands associated with lakes and rivers. Ownership of riparian lands tends to lead towards stabilizing river channels and lake shorelines because the owners do not want to sacrifice part of their holdings to channel migration or shoreline erosion. Furthermore, the increasing tendency to occupy floodplains and seasonal wetlands for agriculture and habitation leads to increased demands for flood control. Thus, the process of development in river and lake basins tends to lead to a hardening of infrastructure that is often reinforced by legislation. Governments tend to reinforce this situation by flood control and river training projects that contribute to the overall degradation of the aquatic ecosystem. In many cases, catastrophic events that are a consequence of river training and authorized building activities that result in the narrowing the river channel and loss of wetlands, are wrongly declared "natural disasters" and lead to further river training and reinforcement measures, with further negative consequences, instead of giving more room to the waters. As a consequence, most land ownership has to be understood and taken into account if any projected habitat improvement activities are to be effective. Furthermore, land may need to be purchased or otherwise reserved for the improvement. A facilitating factor here is the cost of insurance against flood damage on river floodplain and wetland areas, which may become excessive for a society with the result that some seasonally flooded lowlands may be abandoned.

Guidelines – land ownership

i) ***Proper provisions must be made to acquire land or otherwise gain access rights to it in order to undertake restoration or rehabilitation projects.***

2.3 Legal aspects

Proposed habitat conservation or improvement projects may conflict with international, national or civil law or political interests (e.g. fixing border lines between States). Difficulties can arise from three main sources. In the first case, national laws may be based on outmoded views of ecosystem function. Secondly, the requirements for improvement may conflict with national and international laws, interests and agreements granting rights to other users. Thirdly, modifications to the environment may cause damage to other users of the system resulting in civil actions for damages.

2.3.1 International law and agreements

Apart from the various international conventions that oblige signatory countries to take any necessary measures to conserve or rehabilitate inland water environments, there are local regulations that may lay down a context for such activities. For example, the European Union Water Framework Directive requires European member countries to strive towards good ecological status for its rivers and associated lakes. The Convention on Biological Diversity (very often referred to as "Convention on Biodiversity") requires it signatories to "rehabilitate and restore degraded ecosystems and promote the recovery of threatened species, *inter alia*, through the development and implementation of plans or other management strategies". The Ramsar Convention formally extended its principles of aquatic environmental conservation to fisheries at its Ninth Meeting of the Conference of the Contracting Parties to the Convention on Wetlands.

Therefore, the need for responsible approaches to the management of aquatic environments including improvement of aquatic habitats is codified by several international agreements both (i) to contribute to the sustainability of fisheries and (ii) to discharge responsibilities to conserve species diversity. These regulations tend to reinforce any actions to improve the state of aquatic environments. However, other international agreements such as those for supply of electricity from hydropower dams, supply of water or for navigation may well hinder the implementation of rehabilitation or restoration activities. Countries should be careful when entering into new agreements of this type to take into account the needs of aquatic environments that may be affected by the activities concerned.

2.3.2 National legislation

Proposals for improvement of aquatic ecosystems may conflict with local laws either within the agencies responsible for the environment or with other agencies. Thus, laws dealing with navigation, flood protection, drainage or water supply may well prohibit certain changes to the channels of rivers or the removal of levees and dams. In some cases these regulations may be circumvented by using the appropriate technology. In others the statutory obligations may be to answer economic conditions that are now superseded or based on outmoded models of environmental function and could result in changes in the law.

When current legislation does not permit rehabilitation or mitigation measures, consideration should be given to amending or changing the law in favour of fisheries.

Care should be taken to ensure that commercial or private sector interests do not limit mitigation of damage they cause for financial reasons.

2.3.3 Civil law

Actions under civil law may arise where other users of the resource feel that their interests have been damaged by the improvement activity. The case of water abstractions is particularly open to challenge in this way and the setting of environmental flows to conserve fish may well be compromized by court actions to defend existing or future abstraction licences.

Guidelines – legal aspects

i) ***Rehabilitation, restoration projects must be consistent with the laws governing the management of natural resources.***

ii) ***Where these laws are based on outdated concepts of environmental function, efforts should be taken to change them.***

iii) ***Where conflicts exist with laws governing other users of the resource, efforts must be made to make legislation compatible with the interests of the aquatic environment.***

iv) ***They must also be consistent with pre-existing international agreements for power, water supply and navigation. New agreements of this type should take into account needs to conserve or improve aquatic habitats.***

v) ***When current legislation does not permit rehabilitation or mitigation measures, consideration should be given to amending or changing the law in favour of fisheries and aquatic environments.***

vi) ***Care should be taken to ensure that commercial interests do not limit mitigation of damage they cause for financial reasons.***

vii) **Efforts should be made to avoid conflicts with other users of the resource that may lead to civil action.**

2.4 Goals and objectives

Objectives for habitat improvement projects should be clearly stated and prioritized for several reasons:

- The planning process is much clearer if the goals of the project are explicit especially with regard to process and duration.
- The selection of strategies for projects may vary considerably depending on the objectives.
- Costing and financing will vary according to the objectives and the strategies adopted to attain them. It will also become apparent if the objectives can be reached with the resources available.
- Clear statement of objectives is needed to ensure collaboration and participation of other groups in the process and to obtain necessary legal permissions.
- Post project monitoring and evaluation is much simpler if it can refer back to clearly stated objectives.

Objectives are mostly associated with the use that is made of the resource.

The fish resources of inland waters are used for a number of human purposes including food fisheries, recreation fisheries, ornamental fish trade, and conservation. The purpose for which the fish resource is used may influence the approach to rehabilitation. For example, the choice of rehabilitation objectives usually centres on what type of fish community is desired, what is practicable for fishery purposes and what is affordable. Maintenance of the larger, more valuable species generally requires a basin approach, whereas a more localized ecosystem approach may suffice to sustain communities of smaller fish. An increasing number of countries feel the need to satisfy the increasing demand for fish and to compensate for losses on fish production by intensification of fisheries. This usually involves the modification of aquatic ecosystems to integrate with agriculture, typically in rice fields, or to create a form of extensive aquaculture. Recreational fisheries tend to concentrate on relatively few species of particular size and sporting quality – usually predators. In these circumstances, rehabilitation and mitigation efforts concentrate on the habitats occupied by the target species.

Guidelines – goals and objectives

i) ***It is essential that the objectives of proposed rehabilitation projects be clearly formulated and prioritized so that appropriate strategies can be selected. Clear framing of objectives also helps in the funding and execution of individual projects.***

3. ECOSYSTEM ASSESSMENT AND IDENTIFICATION OF REHABILITATION ACTIONS

There are several key steps that must be taken prior to implementing rehabilitation actions including identification of ecosystem conditions, assessment of disrupted watershed processes, identification of rehabilitation opportunities, and prioritization of rehabilitation actions. A brief overview and guidelines are provided and more detailed information can be found in Cowx and Welcomme (1998), Roni *et al.* (2002) and Roni *et al.* (2005). The goals and objectives of the rehabilitation should be established early in this process and revized as additional information becomes available.

3.1 Assessment of Ecosystem Condition

There is a tendency to describe ecosystems as of good or poor quality or potential. Generally this implies that at some stage the system was ideal, usually at a supposedly pristine state. The problem here is that the original state of many aquatic ecosystems, particularly those of the developed temperate zone (Western Europe, Eastern North America), has been so altered that it is often difficult to determine the original predisturbance conditions. Furthermore, the original conditions of many aquatic ecosystems would probably be unacceptable to human societies today. The general fact is that “good” status is usually defined by some social perception of what is desirable for such a lake or river, and social perceptions are likely to vary depending on the social conditions of the region or country.

In order for such judgements to be made the status of target ecosystems must be established as part of the pre-project proposal for any improvement project. This includes identifying the potential of the system based on historic conditions in the area or on reference conditions at undisturbed sites, and the establishment of an ecosystem benchmark based on current conditions and potential for recovery.

Any proposal to improve aquatic ecosystems must be based on assessment of the current state of the river relative to the baseline. This may be done by comparison of the river or lake with historical established conditions, similar systems that may have been designated as benchmarks or by more detailed studies that seek to establish a scientific basis for the classification of the river or lake’s status. A number of tools have been developed to assist in this task. Often these are aimed at establishing flow criteria for the river but can equally be applied to assess the impacts of changes to morphology and river function. Such assessments will also help identify the best approach to habitat improvement and to monitor the effects of the project thereafter. These include examining habitat quality and quantity or using a variety of tools such as habitat suitability indices, habitat quality indices, instream flow models (e.g. IFIM, PHABSIM) or using multispecies indexes such as the indices of biotic integrity or fish species guilds. The latter two, which incorporate a variety of fishes or biota, are particularly useful for assessing condition.

Indices of biotic integrity are designed to indicate the degree to which a watercourse has been impacted by pollution or morphological degradation through a measure of the health of the fish assemblages. The index usually consists of measures of the relative abundance of trophic, reproductive and habitat guilds as well as such information as the number of introduced species. The index from a sampled site can be compared with values from a reference river reach. A score is awarded on the basis of the divergence of the observed from the expected value. The sum of the rating then gives a score for the site. The index is able to integrate data from all ecosystem levels into a single comparable score indicative of the quality of the aquatic resource. Where the natural fish species composition has been disrupted, the fish population (ichthyocenosis) that would normally be present in any waterbody can be deduced from historical records and from the zoogeographical range and habitat of species in surrounding rivers.

In systems where there are numerous species, all of which contribute to the sustainability of the system, it is now common to group the species together into guilds that show similar responses to the environment. These systems lack the predictive precision of some of the other methods but can provide the information needed to generate scenarios of the impacts of changes in morphology and flow on the species assemblages present, as well as of rehabilitation or mitigation activities. Annexes I to III list reproductive, feeding and ecological guilds and their responses to changes in morphology and flow.

3.2 Identification of disrupted ecosystem processes and potential rehabilitation actions

Once an overall assessment of ecosystem conditions has been conducted, two types of question must be answered to identify necessary habitat rehabilitation actions and assist in planning and prioritization (Figure 1). The first type of questions focus on identifying disruptions to ecosystem function and the types of habitat rehabilitation necessary for ecosystem recovery. The second concentrate on how humans have altered habitats and how the habitat changes have affected biota. Addressing these questions requires analysis of natural functioning of aquatic ecosystems, often including assessment of historical habitat types and abundance, as well as assessments of relationships between habitat and biota. These questions help identify where the biological integrity of ecosystems has been degraded and where specific ecosystem processes or functions are disrupted. In combination, these assessments provide a broad understanding of actions that are likely to improve the functioning of aquatic ecosystems, and form the basis of both regional and site-specific plans for ecosystem restoration.

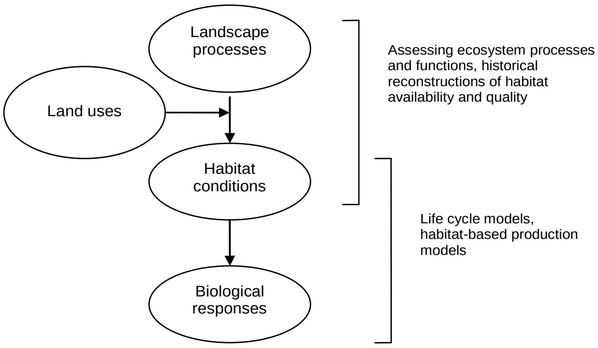

Figure 1. Schematic diagram of linkages among landscape processes, land use and biological responses for assessing disturbed ecosystem functions that identify causes of habitat changes that result in diminished biological integrity and declines in fish populations (modified from Beechie *et al.* 2003).

Assessments of ecosystem functions and biological integrity can be separated into screening assessments that identify areas where ecosystem processes and functions are most impaired, and specific field inventories to diagnose causes of ecosystem impairment and opportunities for rehabilitation. Assessments that correlate landscape and land use characteristics with population attributes can indicate which habitat changes are most likely responsible for declines in specific organisms, and therefore which broad categories of rehabilitation actions are most likely to result in improved ecosystem functioning. Direct assessments of ecosystem processes that form aquatic habitats (e.g. barrier inventories, riparian condition inventories) identify causes of degradation, as well as rehabilitation actions that are required to recover ecosystem functions and biological integrity (Table 3).

Table 3. Examples of landscape processes and functions that should be addressed in planning watershed and river restoration.

Distributed watershed processes
Hydrology – peak flows, low flows, and channel forming flows
Sediment supply – erosion and delivery of sediment
Delivery of contaminants, nutrients
Reach-level processes
Riparian functions – shade, litter delivery, wood delivery, resistance to bank erosion
Channel and floodplain interactions – channel migration, flooding
Habitat connectivity
Blockages to upstream migration (e.g. dams)
Blockages to lateral migration (e.g. levees)

Analysis of habitat change and influences on biota helps predict fish and biota response to habitat changes. Common methods include assessment of habitat change to estimate or model changes in fish populations or other biota and correlation analyses that relate landscape and land use characteristics to fish populations and communities without directly quantifying changes to habitat. These type of analyses do not directly identify causes of habitat degradation or specific rehabilitation actions, but rather provide a means of predicting ecosystem responses to rehabilitation actions (e.g. habitat-based estimates of potential population size for specific organisms), insights into potential changes in species diversity or life history diversity, and a means of identifying which species or populations are most constrained by habitat loss and therefore may be most difficult to recover. Thus, when combined with impaired processes and potential rehabilitation actions developed from the assessments of ecosystem functions and biological integrity, they assist in the planning and prioritization of rehabilitation.

3.3 Prioritization of rehabilitation actions

Once the assessments have been completed, potential actions have been established, and clear restoration goals defined, one can choose from one of several approaches for prioritizing rehabilitation actions depending on the level of information available. An interim approach for setting rehabilitation priorities should be based on an understanding of watershed processes, the basic needs of aquatic biota, and a review of the effectiveness of the techniques available. This begins with the protection of high quality habitats and provision of adequate water quality and quantity. This is followed by the restoration of connectivity of habitats, and of the processes that create and maintain habitat, and finally, if necessary, instream habitat improvements (Figure 2). This section discusses this interim approach and outlines other approaches for prioritizing rehabilitation.

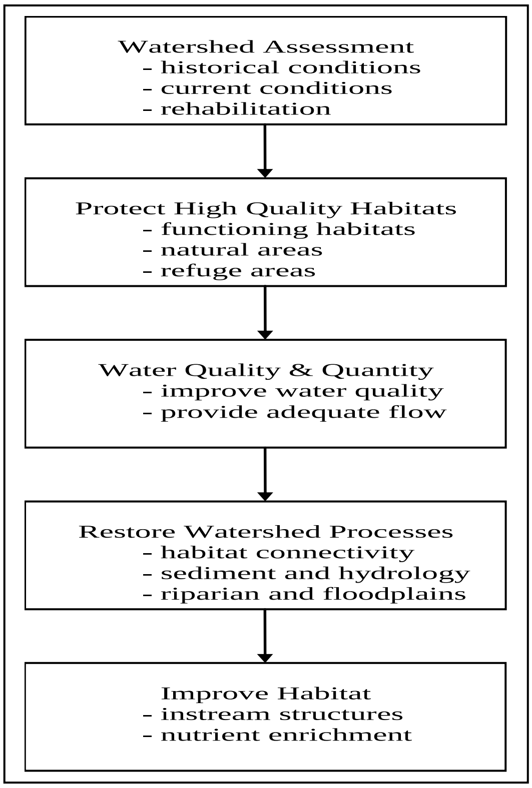

Figure 2. Strategy for prioritizing watershed rehabilitation actions for rivers. The first step (box) is to conduct assessments necessary to determine potential opportunities. From Roni *et al.* (2005).

Habitat protection is typically not seen as rehabilitation. However, given the loss of habitat and the continued degradation from human activities, protecting high quality functioning habitats should be part of the rehabilitation planning process. It is also considered more cost-effective and reliable than trying to rehabilitate habitat once it has been degraded.

Adequate water quality and quantity are fundamental to the success of any rehabilitation action or suite of actions and must be addressed before other actions. In some cases adequate water quality can be achieved through riparian protection or replanting, such as in the case of agricultural runoff. However, pollutants often originate from both point and nonpoint sources including runoff from roads, treated or untreated sewage effluent, or runoff from agricultural lands and will require more complicated measures to improve water quality. Water quantity is typically addressed by limiting the timing and volume of water withdrawals or water use and specific releases from reservoirs. Lengthy political, legal, or legislative acts may be needed to restore water quantity and quality. While both water quality and quantity can be difficult to address, they are critical to the success of other rehabilitation actions.

Restoring connectivity of habitats is the next factor to consider. Reconnection of existing isolated habitat often produces both rapid and long-term results. This includes both restoring longitudinal connectivity such as removal of or providing passage at manmade barriers, and lateral connectivity such as reconnecting isolated floodplain habitats and floodplains – see section on floodplain connectivity and culverts.

Setting up a basin for long-term recovery will require the restoration of natural processes such as delivery of sediment, organic material, nutrients, and other processes. Thus, the next logical step and the factors that most often limit the success of structural manipulations of instream habitat are the restoration of basic hydrologic, geologic and riparian processes.

While considerable effort is focused on structural manipulations of habitat such as placement of boulders and wood, many of which have been successful in increasing local fish numbers, their success is often determined by other factors such as water quality and quantity, habitat connectivity, and watershed processes. Thus, this category of techniques is implemented following, or in conjunction with, improvement of those factors.

In many cases, rehabilitation actions may be focused on one or two species. In watersheds where information exists on factors limiting specific species, a more detailed prioritization of actions is possible.

The prioritization of actions as outlined does not alter the types of actions that are needed to restore ecosystems. Ecosystems restoration will include a wide range of recovery actions affecting the entire life cycles of multiple species. Where a single species is a primary concern, altering the sequence of those actions for rapid recovery of that species might be prudent. The limitation of a single species approach is demonstrated in western North America, where efforts initially focused on rehabilitating habitat for one species of Pacific salmon, but quickly had to change focus when additional species became threatened.

Alternative strategies for prioritizing rehabilitation that incorporate economic, ecologic, and biologic factors have been proposed or used, especially where there are multiple species of concern and prioritizing actions based on the needs of individual species will lead to conflicting priorities. Strategies might prioritize actions on potential increase in fish numbers, cost, cost per fish, aquatic diversity, assuring for guild or populations structure or diversity, or scoring based on a suite of these and other factors. These various strategies incorporate management goals beyond simply restoring watershed or ecosystem processes and habitat. Where at least one species appears to be at high risk of extinction, the refugia approach may be most appropriate to make sure that individual populations are preserved first. By contrast, basins or watersheds with relatively stable populations might embark on the longer term, process-based approach to ecosystem recovery outlined in Figure 2. It is important to note that the sequencing of rehabilitation actions under different prioritization strategies will vary.

Guidelines – assessment and prioritization

- ***i)*** ***Goals of rehabilitation need to be clearly stated at the beginning of the planning and assessment process***
- ***ii)*** ***Several key planning steps need to be followed when assessing ecosystem condition and identifying and prioritizing actions including: identification of ecosystem conditions, assessment of disrupted watershed processes, identification of rehabilitation opportunities, and prioritization of rehabilitation actions.***
- ***iii)*** ***Habitat improvements should be carried out relative to historic, benchmark or reference condition – river, river reach, reservoir or lake. Reference conditions may also take into account the former natural species compositions.***
- ***iv)*** ***To assist in this, countries should create and maintain detailed records of the historical state of their water courses and water bodies.***
- ***v)*** ***The goal or desired state of a river or lake is determined by the current social and economic perception of the environment.***
- ***vi)*** ***Ecosystem condition should be assessed using biotic condition: a generalized guild-based approach is one of the most cost effective of these for areas with a diverse fish fauna.***
- ***vii)*** ***Following assessment of ecosystem condition, on must determine which ecosystem processes have been disrupted and identify appropriate restoration or rehabilitation actions.***
- ***viii)*** ***The method of prioritizing rehabilitation actions will depend on the level of information available, but should initially attempt to address water quality, quantity, habitat connectivity, and processes creating habitat, before attempting short term habitat improvement.***

4. REHABILITATION MEASURES

The following sections describe key issues in rehabilitation and rectification (rehabilitation) measures to address each issue. Initially, water quality and vegetation are discussed as they pertain to rivers, lakes and estuaries. This is followed by a discussion of rehabilitation of rivers and rehabilitation of lakes and reservoirs.

4.1 Water quality

As part of the rehabilitation process any water quality problems that affect the target environment or fish communities should be resolved before any structural rehabilitation projects are implemented. Water quality problems are of four main types:

4.1.1 Pollution

4.1.1.1 Issue

Pollution is the discharge of harmful chemicals into the water. Major sources of pollution are: agriculture, which releases pesticides; livestock rearing that releases toxic dips; industry, which releases a wide range of materials as waste products many of which are highly toxic; mining, which mobilizes a range of heavy metals and other chemicals used in the treatment of ores, and domestic use, which can release pharmaceuticals, detergents and cleaning products. Industrial and mining pollution is more commonly derived from localized sources (point source), whereas agricultural and domestic pollution (and illegal gold mining) can result from numerous small discharges and ground water seepage (diffuse).

Harmful substances can be deposited along with silt on floodplains and in lakes and reservoirs. This means that the toxic effect can persist for many years after the direct source of pollution has been removed. Mining wastes are particularly hazardous in that the spoil heaps are usually contaminated with heavy metals that leach out over many years. This effect means that care has to be taken with any rehabilitation project that remobilizes alluvial deposits.

Depending on its severity, pollution can have a range of effects on fish populations in lakes and rivers. The most extreme events result in large scale fish kills that eliminate all or nearly all of the fish present. Even relatively low levels of contamination may kill eggs and fry leaving the adults more or less unharmed or affect the physiology and sexual composition of the fish. However, prolonged low level (sub-lethal) pollution can result in physical deformation and high incidences of disease. Low levels of pollution may also be sufficient to deter fish from entering contaminated river reaches thereby acting as a chemical barrier to migration. Certain contaminants such as oestrogens for domestic wastes have also been implicated in disturbed sex ratios of some species. Synergistic effects between different pollutants may make them more poisonous to fish even at low levels of individual contaminants. The effects of toxic pollutants are aggravated by the tendency of certain contaminants to accumulate in organisms in the food chain. This means that fish at the top of the food chain, which are often the most desirable for food, carry loads of heavy metals, PCBs or insecticides that may be toxic to humans.

4.1.1.2 Rectification measures

It is essential that discharges of toxic pollutants are controlled for human health and to ensure the sustainability of the fish populations. Most polluting discharges are from readily identifiable point sources and those responsible can be constrained legally through imposition of water quality criteria and the obligation of installing treatment plants. Such legislation should include the Polluter Pays Principle which requires that users of the water and the basin should minimize any deleterious effects, contribute to the mitigation of any impacts of their activities and bear the cost of rehabilitation of the systems when the need for their activity has ceased. The Organisation for Economic Cooperation and Development (OECD) definition of the Polluter Pays Principle is as follows:

1. The Polluter-Pays Principle constitutes for (OECD) Member countries a fundamental principle of allocating costs of pollution prevention and control measures introduced by the public authorities in Member countries;
2. The Polluter-Pays Principle means that the Polluter should bear the expenses of carrying out the measures to ensure that the environment is in an acceptable state. In other words, the cost of these measures should be reflected in the cost of goods and services that cause pollution in production and/or consumption.

Diffuse sources of pollution, such as those arising from widespread agricultural practices, equally need to be brought under control through regulations and education programmes.

4.1.2 Eutrophication

4.1.2.1 Issue

Eutrophication is the process of enrichment of rivers, lakes and reservoirs by the addition of nutrients, mostly phosphorus and nitrogen. Eutrophication is a natural process in many rivers where there is a continuous addition of organic matter as the river flows down stream. Two major human activities are the major source of nutrients: agriculture, which uses considerable amounts of fertilizers that are washed or diffused into water bodies through both surface runoff and ground water seepage; and sewage which contains not only faecal matter but also detergents and other waste products of day-to-day living. Other sources include livestock rearing where large amounts of animal excreta may be washed into nearby waters and aquaculture where direct enrichment of the water occurs before it is redischarged into adjacent waterways. The effect of eutrophication depends on its intensity. It operates on the environment in two main ways.

Firstly, it has a biochemical oxygen demand (BOD) that absorbs oxygen from the water and thus lowers the amount available to fish. Secondly, the various organisms in the phytoplankton are very sensitive to nutrient levels. Low nutrient levels are usually equated with green algae and diatoms whereas high nutrient levels favour blue-green algae. This, in turn, has several effects. Most phytoplankton eating fish feed on green algae, desmids and diatoms and tend to decline in abundance and disappear as these are replaced by blue-greens. This shift in species composition is only part of a general shift as species that are less resistant to low dissolved oxygen concentrations decline in abundance in favour of more resistant species. The dense algal populations that occur at high nutrient concentrations can reduce the transparency of the water, shading out submersed vegetation. Dying algae sink to the bottom and may contribute to the high BOD as well as choking bottom substrates.

Artificial enrichment of water bodies to obtain higher productivity is used in intensified systems where extensive forms of culture are practiced or in some very oligotrophic waters.

4.1.2.2 Rectification measures

The objective of eutrophication control is not to eliminate all nutrients from the water, as this can be negative in its effects because some nutrients are always necessary to support life. Rather, control should concentrate first on the reduction of nutrients to a tolerable level followed by constant fine-tuning to maintain levels at those optimal for the target fish communities.

Point source discharges of nutrient enriched waters need to be controlled through a combination of regulations and treatment plants. In the case of lakes, which are particularly susceptible to nutrient enrichments discharges of nutrient rich waters from treatment plants should be made into water course outside the drainage of the lake concerned. Diffuse sources of nutrients are far more difficult to deal with as these result from widespread lifestyles associated with agriculture and domestic habits. Here, limits need to be set for fertilizer use in agriculture, modes of discharge of wastes from livestock concentrations and for human waste disposal procedures by septic tanks or other measures. Attention needs to be paid to the risks of contamination of ground waters as well as to direct discharges from surface run-offs. In small lakes the deoxygenating effects of eutrophication can be combated by aeration especially in intensified systems with extensive aquaculture approaches. In many cases a riparian fringe of trees or soft vegetation will remove most of the nutrients from surface and near surface flow derived for agriculture.

Nutrient concentrations can also be controlled by manipulation of the food webs within lakes, reservoirs or fragmented river reaches. In these instances the ultimate goal of food web manipulation is to reduce the biomass of phytoplankton. Such manipulation is based on two approaches.

Firstly, pelagic species that eat phytoplankton directly alter its abundance. Increases in abundance of these species will decrease the quantity of phytoplankton thereby converting the excess productivity into fish flesh that can be caught and removed from the system. The situation is more difficult to manage where complex food webs are involved. Species that eat zooplankton influence the size and abundance of the zooplanktonic organisms. Many fish species are selective for the size of zooplankters they eat, and the zooplanktonic organisms themselves prey on different types of phytoplankton. Thus, changes in the numbers of zooplankton feeders will indirectly change the abundance and composition of the phytoplankton. Furthermore, piscivorous species prey on plankton feeders and influence the abundance of both phyto- and zooplankton feeders.

Secondly, benthic feeders recycle bottom material by releasing nutrients trapped in the sediment through physical disturbance of the bottom, and through their own excretion. Dense populations of species such as carp can also so muddy the water that bottom macrophytes cannot develop. Removal of species that disturb the bottom in this way can lead to increased amounts of nutrients being stored in bottom deposits.

4.1.3 Siltation

4.1.3.1 Issue

Many land use practises including agriculture, forestry and mining result in increased sediment loads in rivers. This disturbs natural erosion-deposition cycles resulting in faster filling-in of floodplain water bodies, lakes and reservoirs. Deposition of sediment banks in river channels may lead to the raising of river channels above the surrounding land with increased risks of flooding and channel migration. It also leads to choking of bottom gravels with negative effects on reproductive capacity of lithophilic species and declines in abundance of food for bottom feeding fish. High levels of silt also reduce transparency of the water resulting in the disappearance of submersed vegetation and can even have direct lethal effects on the fish.

4.1.3.2 Rectification measures

Siltation can only be contained by rigorous controls over land use practices including forestry and agriculture. Prohibition of clear cutting in forestry, adoption of improved ploughing techniques in agriculture and the maintenance of a riparian fringe of vegetation can go a long way to reducing the amount of topsoil washed into waterways. In the case of mining, sedimentation dams are usually installed to prevent the major sources of sediment reaching the adjacent waters.

4.1.4 Temperature

4.1.4.1 Issue

Temperature may either be raised by land use changes resulting in changes in riparian condition, sediment supply and channel conditions or thermal pollution. Thermal pollution occurs where rivers or lakes are heated beyond their normal limits by discharges from human activities. Most of these are associated with raised temperatures below power stations, where limited reaches of rivers are warmer conditions maintained. This has effects on fish stocks whereby localized stocks of warm water exotic species may occur. Lowered temperatures may result from the discharge of bottom waters for deep reservoirs. These can persists for some distance downstream and have localized effects on the survival of the fish present.

4.1.4.2 Rectification measures

Thermal pollution is usually of fairly localized significance and has little impact on the morphological conditions in a river. Increased temperatures due to land use can be addressed by rigorous land use changes (similar to siltation) and protection and rehabilitation of riparian areas (see also section on vegetation).

Guidelines – pollution

i) Rehabilitation of inland waters should only be carried out in parallel with measures to improve water quality or after any water quality problems affecting the fish stocks or the environment have been resolved.

ii) Toxic substances can remain trapped on floodplains, in lakes and reservoirs and in mining spoil heaps for many years after the polluting activity has ceased. In such cases care must be taken not to remobilize the pollutants when executing rehabilitation projects.

iii) Discharges of toxic pollutants should be strongly regulated and subject to the Polluter Pays Principle.

iv) Point source discharges of nutrient enriched waters should be controlled through regulations and treatment plants. Where possible, nutrient rich waters from treatment plants should be discharged outside the drainage of lakes. Limits need to be set for fertilizer use in agriculture.

v) Siltation should be contained by rigorous controls over land use practices including forestry and agriculture.

4.2 Vegetation

4.2.1 Issue

Vegetation is an essential part of aquatic environments. Its distribution, abundance and composition have been altered by human activities either detrimentally or beneficially to fish and fisheries. Proper management of vegetation has advantages for the fishery and is an integral part of river and lake rehabilitation. It is therefore considered here as a separate issue and specific aspects of vegetation in rivers and lakes will addressed in the appropriate sections.

Aquatic vegetation may be classified by habit into phytoplankton, submersed vegetation, emergent vegetation, floating vegetation and woody debris.[2] It may also be classified according to its position in the system: instream, floodplain, swamp or riparian vegetation.

4.2.2 Importance of vegetation

Vegetation is an integral part of aquatic ecosystems and contributes a number of essential services to the ecosystem and to human societies.

Phytoplankton is an essential basis of food chains in lakes and potamonic zones of rivers as well as being essential food for zooplankton that forms the diet of many of the younger stages of many species of fish. Equally important as fish food are the dense growths of epiphytic algae and associated organisms that form biofilms on the stems and roots of other types of aquatic vegetation.

Higher vegetation in the form of trees, bushes and reeds stabilize bank and shoreline structures. Their root masses bind the soil together and protect against erosion by currents. Reed beds and floating masses of grasses protect river banks and lake shorelines against wave action, either natural or induced by navigation. Fallen tree parts block channels, impound and redirect water, collect floating debris and generally contribute to the instream structure, particularly of small headwater streams.

Trees in the riparian zone group together to form riparian forest strips along the banks of rivers and the shoreline of lakes. Riparian woodlands play an essential role in shading and cooling the water. Shading can regulate production with far less phytoplankton and submersed vegetation being produced in heavily shaded areas. Their root masses and associated vegetation communities provide habitats and structure for breeding, nursery sites, shelter and refuge. Many small fish species live entirely within the complex habitat structures of these marginal zones. Floodplain forests are important to certain specialized fish communities whose breeding, nursery and feeding cycles may even be linked to specific types of tree. Mangrove forests in the lower reaches of rivers and their associated coastal lagoon provide essential spawning, feeding and nursery habitats for a wide variety of brackish water and marine aquatic organisms.

Riparian vegetation plays a fundamental role in the nutrient cycle of rivers. Leaf fall and the fall of organism associated with the tree canopy join similar organic matter washed in from the land to form the basis of the

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[2] See glossary for definitions.

nutrient cycles of rivers, especially in the numerous small headwater streams. The process of gradual disintegration of the coarse organic matter upstream to ultra-fine organic particles downstream by a succession of insects and other organisms is described by the river continuum concept.

In addition to the generalized role as nutrient inputs to aquatic systems, marginal vegetation is a direct source of food to fish and other aquatic wildlife. Fish that eat higher vegetation directly are comparatively rare, although species that specialize in seed, fruit and insects that fall into the water from the vegetation are more common. Furthermore, the stems of emergent vegetation and the root masses of floating aquatics become coated in films of periphyton that are the preferred food of the young of many species. Aquatic vegetation also provides food for humans and fodder for their animals and many riparian communities subsist through the flood with support from floating aquatics.

Vegetation contributes to the self-purifying capacity of rivers and lakes. Submersed vegetation contributes to oxygenation of the water. Submersed, floating and emergent vegetation may grow strongly in eutrophicated conditions and can be removed from small systems to aid in lowering nutrient concentrations. Riparian vegetation, especially strips of forests along shorelines or river banks, remove a large percentage of the nutrients from ground water seepage and surface run-off.

4.2.3 Problems with vegetation

Vegetation poses a number of problems especially in highly controlled systems. Excessive nutrients can produce phytoplanktonic blooms that shade out other vegetation and contribute to lowered oxygen concentrations in the water. Choking of shallow streams and rivers by emergent vegetation raises risks of flooding during the earlier part of the autumn floods in the temperate zone. Invasions and catastrophic expansions of floating aquatic weeds can cause serious problems, especially in lakes. Extensive mats of *Eichhornia*, *Azolla*, *Salvinia* or *Pistia* have all caused serious problems in Lake Kariba, Lake Victoria and many other areas into which they have been introduced, where the vegetation may become so thick as to impede navigation and localized de-oxygenation under the mats rendered large areas virtually fishless. In smaller watercourses excessive riparian trees can shade the water so that instream vegetation and phytoplankton cannot grow. Excessive and uncontrolled riparian vegetation can impede access by fisher folk and by villagers searching for water. It can also detract from recreational uses such as angling or hiking.

4.2.4 Control of vegetation

Such are the problems caused by invasive plants that a considerable amount of effort is devoted to their control and elimination. The principal methods are:

4.2.4.1 Mechanical

Mechanical control consists of cutting, dredging or removal with grabs. It is rarely effective over large areas because of the rapid growth of invasive plants, the expense and effort needed and the fact that mechanical removal fragments the plants further and most are able to grow vegetatively from the parts that are left. Log booms and barriers may be use to keep the weed out of certain areas. Mechanical methods are used mostly to clear river channels and access to boat landings and to water intakes.

4.2.4.2 Chemical

Spraying with herbicides is commonly used to clear large areas of weed. Chemicals such as 2,4-D, Diquat and Endothal have been used with success. However, large-scale dosages with herbicides can poison fish and the organisms they feed on. Chemical treatments have the additional disadvantage that the decaying plants fall to the bottom and create anoxic conditions. Chemical methods are, therefore, appropriate to highly controlled situations such as the preparation of small lakes for extensive aquaculture.

4.2.4.3 Biological

More recent attempts at vegetation control have concentrated on biological methods. These usually involve the introduction of an animal or plant that acts as a control on the invasive species in its natural range. Some fungi and a range of insects have proved successful in some circumstances (see Table 4).

Some fish, particularly grass carp *Ctenopharyngodon idella* have also been used with success to control soft plants such as *Hydrilla*. In such cases sterile triploid individuals are often used to avoid the risk of the species breeding in its site of activity although grass carp only breed in certain highly specific riverine environments.

4.2.5 Use of aquatic and riparian vegetation to benefit fisheries

The importance of vegetation as habitat for many aquatic organisms means that the proper management of vegetation associated with aquatic ecosystems is an essential part of the conservation and rehabilitation of aquatic ecosystems. Management of the vegetation can be used to benefit selected fish species and communities. Several types of vegetation are particularly important. Adequate but not excessive quantities of submersed vegetation should be maintained, although careful management of instream vegetation may be necessary to avoid interference with flow. It may also be necessary to remove excessive riparian trees to avoid excessive shading of the river bed. Riparian trees and bushes should be conserved or restored, although careful control should be exercised to avoid excessive shading. Copses or larger areas of trees should be maintained on the floodplain especially in naturally forested rivers. Mangrove woodland should be conserved or restored in the lower reaches of tropical and equatorial rivers and their associated deltaic and coastal lagoon systems. In some rivers and lakes, artificially constructed brush and vegetation parks can be used as refuges, and breeding and feeding substrates to compensate for losses in natural riparian and instream vegetation.

Table 4. Examples of insects used for the biological control of invasive vegetation.

Plant	Control agent
Alternathera philoxeroides [Alligator weed]	*Agasicles hygrophila* [Alligator weed beetle]
	Amynothrips andersoni [Alligator weed thrip]
	Vogtia mallori [Alligator weed stem borer moth]
Eichhornia crassipes [Water hyacinth]	*Neochetina eichhorniae* [Weevil]
	Neochetina bruchi [Weevil]
	Saneodes albiguttualtis [Moth]
Hydrilla verticulata [Hydrilla]	*Hydrellia pakistanae* [Leaf boring fly]
	Hydrellia balcuinasi [Leaf boring fly]
	Paraoynx diminutalis [Moth]
Pistia stratiotes [Water lettuce]	*Neohydronomous affinis* [Weevil]
	Spodoptera pectinicornis [Moth]

4.2.6 Use of vegetation to replace heavy engineering solutions

The capacity of certain types of riparian vegetation to stabilize and protect river banks and lake shores is useful as an alternative to hard engineering solutions such as concrete, rip-rap or gabions to revet banks shorelines. Natural materials such as logs or trees can be used instead of hard structures for river training structures such as deflectors and weirs. Usually the living material is more aesthetically pleasing, better dated to the needs of the aquatic fauna, costs less, can adapt to changing conditions within the aquatic system and is more readily incorporated into the rehabilitation process. However, in situations where there are extreme flows and turbulence they may be less effective.

Guidelines – vegetation

i) ***Vegetation is an integral part of aquatic ecosystems and contributes a number of essential services to the ecosystem and to human societies*.**
ii) ***Vegetation may cause problems if uncontrolled so programmes for its removal or control may be necessary.***
iii) ***Degradation or removal of critical vegetation can damage the functioning of the environment and the services it delivers, so restoration of certain vegetation, such as wooded riparian strips, may be necessary.***
iv) ***Where control of aquatic vegetation is necessary, mechanical methods are appropriate to smaller river channels but biological methods are to be preferred for larger scale eradication and control. Chemical methods should be avoided except in exceptional circumstances.***
v) ***Dead wood is a crucial element in many types of upland river environment and should be restored from areas from which it has been removed.***
vi) ***Rehabilitation techniques using natural vegetation are to be preferred to hard engineering solutions in many circumstances and should be used wherever possible.***
vii) ***Critical vegetation should be conserved or restored to protect vegetation dependent species.***
viii) ***Natural materials such as rocks and logs should be preferred for the construction of protection and training structures wherever possible.***

4.3 Rivers

Proposals for river rehabilitation must be based on a thorough understanding both of the morphology and physical functioning of rivers, and on the biology and ecology of their fish populations. Where ever practical a whole basin approach should be adopted although it is recognized that most rehabilitation activities will occur at a local scale.

4.3.1 Morphology

Any river has a tree-like branched form with numerous small streams that coalesce progressively into fewer, larger rivers and eventually form a single major channel. In consideration of this, streams are often awarded an order with the smallest streams being order one to the highest orders – 11 to 13 – applying to very large rivers. The various components present a continuum of changing channel form that depends primarily of the distance from the source, the slope and the type of rock over which the river flows. The form of the river channel, its associated floodplains and its estuarine or deltaic region is determined by erosion and depositional processes that are conditioned by these factors. In most rivers there is a greater variety of channel form within any one river than there is between rivers, and equivalent sectors of different rivers are sufficiently similar as to make their categorization possible. There have been several attempts at categorizing rivers by dividing them into characteristic sectors. The earliest attempts at classifying rivers into youthful, mature and old age groupings were based on adjustments along their course and roughly corresponded to mountain, highland and lowland locations. Other common classifications are based on ecology, such as the division of the river into Creon, Rhithron (epi-, meta- and hypo-rhithron) and Potamonic (epi-, meta- and hypo-potamon) zones by Illies and Botosaneanu (1963) and used mainly in Europe; and the more recent morphological classification by Rosgen (1994) and Montgomery and Buffington (1997) (see Annex IV) derived mainly for North American and New Zealand systems and based mainly on slope. Both classifications can be applied outside their areas of origin as descriptors and to indicate baseline conditions in modified systems. For reasons of simplicity the following classification is used in these guidelines (Table 5).

4.3.2 Fisheries ecology of rivers

Each of the channel forms contains a large number of habitats (Annex V). Rivers contain a large number of species that are adapted to the many different types of channel form, flow regime and individual habitats (see Annexes I to III and V). Some species are static and move little for a specific habitat to which they are frequently highly adapted. Others move between different habitats of which the following are particularly important:

Spawning sites: Usually substrate and current dependant – rock, gravel, sand or submersed vegetation according to the spawning guild of the fish (see Annex I).

Nursery sites: Usually shelter dependant – shallows, floating and submersed vegetation, backwaters and floodplain lagoons.

Feeding sites: Usually correlated with abundance of food organisms – principally riffles, detrital substrates, floodplains (see Annex II).

Shelter: For shelter from predation, from strong currents and from adverse condition such as low dissolved oxygen or excessive temperature – permanent floodplain pools, pools in highland rivers, deeps in lowland rivers, backwaters, submerged woody debris (see Annex III).

Connectivity: Pathways to communicate between the other habitats – main river channels, connecting channels between floodplain and river channels (see Annex III).

Table 5. Simplified classification of river channels used in these guidelines.

Classification	Description	Corresponding channel type: Age	Illies and Botosaneanu	Rosgen	Montgomery and Buffington
Montane	• Steep, • Deeply entrenched Dominated by waterfalls and plunge pools • No floodplain Rock and boulder substrates	Youthful	Creon	Aa+	Cascade, step pool
Highland	• Moderate slope Slightly entrenched Dominated by pool-riffle structures • Limited or no floodplain • Cobble to gravel substrates	Mature	Rhithron	A, B F, G	Step pool, pool riffle, forced pool riffle
Lowland	• Shallow slope Slightly entrenched Dominated by meandering or braided channels • Often extensive floodplains • Sand to mud substrates	Old age	Epi- and meta-potamon	C, D, DA, E	Pool riffle, forced pool riffle, dune ripple
Estuary and coastal wetlands	• Very shallow slope • Often deltaic with numerous distributaries channels • Mud substrates • Often extensive floodplains with associated tidal salt marshes • Often associated with coastal lagoons.	Senescence	Hypo-potamon	DA	Dune ripple

Guidelines – fish ecology

i) ***River rehabilitation must be based on a thorough understanding both of the physical functioning of rivers and on the biology and ecology of their fish populations.***

ii) ***River rehabilitation should aim to conserve the large number of species that are highly adapted to the variety of habitats in the river and its associated floodplains, lakes and reservoirs.***

4.3.3 Flow

Flow, in the sense of the amount of water passing through the river at any instant in time is one of the most important conditioners of river ecology. It operates mainly:

- Directly on fish through their physiology acting as a trigger for migration and ripening.
- Indirectly though its action in forming rivers by controlling the erosion-deposition activities that create and maintain river habitat structure.

4.3.3.1 The nature of flows

Flow is generally expressed as a hydrograph that traces the quantity of water flowing down the river at defined intervals during the year. The water derives from the precipitation falling within the river basin over the year. The type of precipitation influences the form of the hydrograph. Hydrographs based on melting snow and glaciers are generally delivered some time after the main time of precipitation and are smoother than those arising from rainfall. Rainfall-derived hydrographs respond much faster to precipitation events and introduce the concept of “flashiness”. Flashy rivers are those that respond rapidly to localized rainfall to form short but intense spikes of high in the hydrograph. Generally the smaller the river basin the flashier the river whereas larger rivers average out the contributions of numerous tributary streams to form increasingly smooth, stable and predictable flood curves.

Flow interacts with fish fauna in a number of ways principal among which are:

- ***Population flows***: Flows that influences the amount of fish present though density dependent interactions with individual population parameters such as growth and mortality. Major criteria here are the quantity of the high and low season flows and the amount of water in the river at any one time.
- ***Critical flows***: Flows that trigger events such as migration and reproduction. Here the main criteria are timing and quantity of flow events.

- ***Stress flows***: Flows that endanger fish because of excess velocity at high water or through desiccation at low water. These are typically extreme flows and are also known as channel forming flows as the majority of the modification to channel structure occurs at these exceptional events.
- ***Habitat flows***: Flows that are needed for the maintenance of environmental quality including depth and connectivity, temperature, dissolved oxygen levels, sediment transport and such functions as cleaning and aeration of spawning gravels.

Fish species at any part of the river are adapted to the natural flow regimes existing there and generally require particular aspects of the hydrograph for their survival. For example, in highland rivers flashy flood peaks are needed at specific times of the year to clean spawning gravels and to induce fish to migrate. At the same time sufficient background flows are needed to prevent the river from drying out and to make passage possible for migrating fish. In lowland rivers, fish populations depend much more on smooth but strong flows that gently inundate the floodplain, scour material from floodplain features and deposit silt at others. The regular connection of the floodplain is also necessary for fish to access the plain for breeding and growth. So important is this seasonal connection that there is a close connection between the depth and duration of flooding and the fish catch in the same or following years.

In all rivers, a number of features of the hydrograph are important to fish as described in Table 6. For further information on flood regimes and their impacts on fish see Poff *et al.* (1997); Bunn and Arthington (2002); and Welcomme and Halls (2004).

4.3.3.2 Issue

Human modifications to natural flow regimes by damming, hydropeaking (the alternation of high discharges with channel dewatering resulting from the operation of hydroelectric dams) and water abstractions is changing the nature of rivers by destroying habitats, altering channel form and interrupting connectivity. They also alter fish assemblages by suppressing flow sensitive species and favouring ones that are able to cope with changes to flow regimes.

Table 6. Effects of changes in characteristics of flow regimes on fauna and flora in highland and lowland rivers.

Flow characteristic	Change	Effect on fauna and flora
Timing *The time at which peak flows occur either as spikes or as smooth flood curves*	Change in arrival of flow peaks (usually a delay in arrival)	• Influences physiological readiness of fish to mature, migrate and spawn • Desynchronises maturation of drifting larvae and movement to floodplains and backwaters • Influences thermal coupling between flood and temperature of the water
Continuity *The continuity of flooding – generally high in large and lowland rivers and less so in small highland streams*	Interruption to flood	• Stranding of fish in pools • Exposure of spawning substrates with stranding and desiccation of eggs • Failure of eggs and larvae to colonize floodplain in lowland rivers • Increases exposure to predators
Smoothness *The discreteness of flood events – whether high flow arrives as a series of discrete events or a smooth curve*	Increased flashiness	• Exposure of nests and spawning substrates with stranding and desiccation of eggs or larvae • Inability to form a sustained flood in lowland rivers
Rapidity of change *The speed with which the flow changes from high flow state to low flow state*	Overly rapid rise in level Overly rapid fall in level	• Submergence of nests and spawn in too great a depth • Failure of floodplain vegetation to grow or killing of developed vegetation • Increased stranding mortality of fish in temporary pools in the channel and on the floodplain
Amplitude *The intensity of the flood curve at any time usually translated as increases and decreased in depth*	Decreased level in main channel during dry sea-son Increased level and excessive flow in main channel Increased or decreased depth of flooding on floodplain	• In highland rivers less volume in the river to support fish populations • Smaller refuges for fish • Increased risk of anoxia in main channel and floodplain pools • Greater mortality in main channel through competition and predation. • River depth may not pass bankfull resulting in failure to flood • Washes away eggs and larvae from upstream sites • Can sweep drifting larvae past suitable nursery habitats in floodplains and backwaters • Fewer floodplain water bodies connected to main system

Flow characteristic	Change	Effect on fauna and flora
		• Less space for reproduction, refuge and feeding of young and adult fish during flood • Lower floods mean less area for food for growth of fish
Duration *The time that the high flow event takes*	In lowland rivers -reduced time when floodplain submerged In lowland and highland rivers – reduced duration means increased time of dry phase in main channel	• Less time for fish to remain in flood-plain refuges and therefore less time to grow and store fat for the low water season • Greater exposure of fish to negative conditions in main channel • Greater risk of desiccation of main channel, backwaters and floodplain waterbodies • Greater exposure to fishermen and predators

4.3.3.3 Environmental flows

The concept of environmental flows is that sufficient flow be maintained in a river to sustain its ecological functions including any fish populations that are present.

It is important to make legal provisions for the control of both the abstraction of water from river channels for agriculture, urban use and industry and the release of impounded waters from dams so that environmental flows are respected in river channels and floodplains are inundated annually to the maximum extent possible.

A number of methods have been proposed for the assessment of what flows are needed to fulfil the conditions for environmental flows (see Tharme, 2003 for example) but these have been developed mainly in relatively small, highland, salmonid rivers and only recently has greater attention been paid to development of assessments for larger lowland systems.

Ideally, assessment methods should be based on a high degree of technical knowledge and research about the target system and its fish populations. Unfortunately, this is not possible in most circumstances because of the cost and the lack of essential information. Methods, therefore, tend to be based on expert opinion delivered through some form of framework.

In general, procedures for the assessment of the water requirements of fish in rivers should:

- take into account the complexity of ecological requirements of all life stages of fish in rivers;
- be easy to understand and use;
- be cost effective;

- be compatible with expertise available;
- be legally robust;
- be generally accepted by all levels of fisheries and water user stakeholders.

It is generally insufficient that environmental flows be calculated only in terms of the total amount of water available to the system as a percentage of yearly flow, as is the case with some of the simpler assessment methods, but also should respect critical features of the hydrograph such as timing and the shape of the flood as set out in Table 6.

General principles to be taken into account in deriving environmental flows are:

Wet season – flood phase

In highland rivers

- Sufficient water should be made available at the appropriate time for the cleaning and conditioning of spawning gravels and for the correct passage of water for aeration of developing eggs and fry.
- Flood releases should correspond to the needs of fish for hydrological stimuli for migration and spawning.
- Extreme events that result in wash-out of adults, juveniles and drifting fry should be avoided.

In lowland rivers

- A flood must be induced, preferably every year but if not every year then at least with sufficient frequency as to allow all species to reproduce within their life spans.
- The area flooded should be as extensive as possible over a period of years and consistent with year-to-year variations in flood height.
- Flood releases should correspond to the needs of fish for hydrological stimuli for migration and spawning.
- Flood releases should be timed to arrive after the wetting of the floodplains by local rainfall. This means that the water volume is used to maximum efficiency in flooding rather than in saturating the desiccated soils of the floodplain.
- Flood curves should be as smooth as possible to avoid repeated advances and withdrawals of the water that strand and desiccate eggs adhering to marginal vegetation and nests.
- Rises and falls in level should be relatively slow. This should avoid over-rapid submergence of nesting sites, and failure of vegetation to adapt and grow in the rising phase and stranding during the falling phase.
- High short floods should be alternated with lower but longer ones on a year-to-year basis to favour all groups of species.

- Extreme events that result in wash-out of adults, juveniles and drifting fry should be avoided.
- The special requirements of species spawning upstream in the main channel whose juveniles drift downstream and onto the floodplains should be taken into account as they are particularly sensitive in terms of the timing and intensity of the flood.

Dry season – drawdown phase

- Adequate dry season flows should be assured to allow for sufficient connectivity for migration.
- Adequate amounts of water should remain in the river as this is critical to the survival of the fish population. Prolonged period of drought can lead to deoxygenation of the water and even desiccation of the channel allowing it to dry out into a series of isolated de-oxygenated pools.

Guidelines – flow

i) ***Projects and interventions in river basins that are likely to alter the amount of water available to the river and the timing of the delivery of the water should make arrangements to release the flows necessary for the maintenance of healthy fish populations.***

ii) ***There should be statutory regulation of a) the amount of water abstracted from rivers and b) the amount and pattern of releases of water from impoundments in conformity with the environmental requirements of fish and other living aquatic organisms.***

iii) ***Environmental flows should be based on systematic assessments; should not be determined solely on the basis of a percentage of total annual flow and should take into account the specific seasonal needs of the fish species that are present.***

4.3.4 Measures for the rehabilitation of rivers

The section provides an outline review of the main methods that have been used to rehabilitate rivers. Greater technical details are available in selected publications – ***North America*** (Slaney and Zoldakas, 1997; FISRWG, 1998), ***Europe*** (RSPB *et al.*, 1994; Cowx and Welcomme, 1998; Lewis and Williams, 1984; The River Restoration Centre. http://www.therrc.co.uk/manual.php; Summers *et al.,* 1996), ***Australia*** (Rutherfurd *et al.*, 2000), and ***East Asia*** (Parish *et al.*, 2004) that are applicable to many regions throughout the world.

4.3.4.1 Caveat

Methods are likely to be system and fish community specific. They should thus be based on a thorough understanding of the habitat requirements of the fish species and communities present in the target river. Not all the methods listed here may be of use in any particular system. Most of the experience with river restoration to date has been accrued on salmonid streams in the temperate zone and Armstrong *et al.* (2003) indicates the level of habitat information about salmonid species that is available. However, experience in other regions of the world, with other fish communities is increasing and there is growing literature on the subjects. As new types of systems are proposed for rehabilitation, new approaches and methods will need to be developed.

Many methods for rehabilitation and mitigation require artificial inputs in the form of structures or material added to the system. In areas where immediate restoration or rehabilitation is possible it is better to use approaches and allow natural erosion and deposition processes, and the accompanying succession of vegetation colonisation and growth to complete the work.

If suitable conditions have been restored in a river, fish may recolonize a rehabilitated section or river stretch, however it cannot be assumed that this will always occur. Desired species must be present somewhere in the connected river/stream system, and have good access to the rehabilitated section. Monitoring the section for occurrence of target species is necessary and if recolonization does not occur over a period of time, then other interventions such as stocking may be necessary to facilitate recovery.

4.3.4.2 Issue

Human interventions, by damming, water abstraction, flood control, land reclamation and river control works alter the channel and floodplain form and function drastically, shifting any reach of river into another category or, as commonly, changing the natural channel from a rich tapestry of habitats to a type of featureless and monotonous channel divorced from its floodplain not found in nature. These changes threaten many species with extinction and shift the balance of fish communities for specialized to generalized species. The principle goal of river rehabilitation is to restore the habitats and the connections between them.

4.3.4.3 Aims

The main aims of river rehabilitation are to reintroduce:

- longitudinal and lateral connectivity;
- habitat complexity;
- diversity of depth, flow, substrate and riparian structure; and
- through these ecological processes and services.

In the following subsections we discuss restoration of highland and lowland rivers, recognizing that many issues and interventions can be common to both types of rivers.

Guidelines – general river rehabilitation

i) ***Methods for rehabilitation are likely to be system and fish community specific. They should thus be based on a thorough understanding of the habitat requirements of the fish species and communities present in the target river. Not all available methods may be of use in any particular system. New approaches and methods will need to be developed as new types of system are proposed for rehabilitation.***

ii) ***If suitable conditions have been restored in a river, fish may recolonize a rehabilitated section or river stretch, however it*** *cannot* ***be assumed that this will always occur. Desired species must be present somewhere in the connected river/stream system, and have good access to the rehabilitated section.***

iii) ***Soft engineering approaches using natural processes are to be preferred to hard engineering solutions wherever possible***

4.3.5 Highland rivers

4.3.5.1 Issue

Highland and montane rivers have been modified by a series of activities including road construction, forestry activities, dam building, gravel extraction, river straightening for flood protection and fragmentation by weirs and dams. These activities have resulted in the loss of habitat structure and a lessening of the river's capacity to support both resident fish and migratory species that use highland rivers to breed.

4.3.5.2 Main aims

The aims of rehabilitation and mitigation activities on highland rivers are mainly to:

- restore pool-riffle structure;
- improve channel diversity;
- ensure provision of adequate cover; and
- provide appropriate vegetation.

4.3.5.3 Pool riffle sequences

Conservation of pool-riffle sequences depends on the sediment load and the hydrological regime of the river. Pool riffle sequences occur in the channel on average over about seven channel widths. Depending on the slope of the channel they may be interspersed with other channel forms such as waterfalls and rapids, featureless glides, or meandering reaches.

Reconstruction of riffles. In rivers where sediment loads are high, usually because of bad land-use practice upstream, the structure of riffles is constantly under threat of degradation by deposition and filling of the gravel substrates with sediment. This can be remedied by improvements of the land-use practices in the basin, by arranging for flushing flows to be released from upstream dams at times consistent with the needs of the fish fauna or by placement of weirs or deflectors to locally increase flow and so keep areas of gravel free of sediment.

In rivers downstream of dams where sediment loads are severely reduced by hydropeaking or sediment retention, erosion of the gravel substrates may occur. In these cases mitigation of the effect is usually by physical replacement of the gravel. In some cases, this is done by simply tipping large amounts of gravel into the stream and either rearranging it mechanically or letting the current redistribute the material. Greater control is exercised in moderate sized streams by rubble mats, where the river bed is covered by an impermeable membrane that is then top-filled with gravel. Unfortunately, when the cause of the erosion is not removed this has to be a repeated process and is likely to be costly. Furthermore, riffles have a natural tendency to migrate downstream so the artificial gravel reaches may be anchored at their lower end by a weir or boulder dam. Another way to avoid this problem is to create off-river gravel bottomed spawning sites linked to the main river by a biocanal.

Where the sediment load is not too severe, riffles can be recreated using the deposition and erosional capacity of the flow. To do this, deflectors, vanes or weirs have to be placed across the river to create local differences in flow that result in a sequence of pools and gravel bars. Structures such as deflectors, vanes or weirs can be constructed of stone, boulders, logs, gabions or concrete. In some cases vegetation, particularly trees, can be used to deflect current.

Reconstruction of pools. The deeper, still waters of pools are a necessary component of pool-riffles sequences. They provide a varied habitat for resident species and resting areas for migratory fish on their journey upstream. They are affected by silting and channel engineering works and need to be rehabilitated in modified systems to complete the essential habitats of highland rivers.

Pools can be restored by similar means to riffles, using artificial structures such as notched or blockstone weirs, deflectors, vanes, logs or logjams. In many cases the two types of habitat emerge together with deeps excavated by accelerated current alternating with gravel shallows in slack areas behind the obstruction.

Pool and riffle restoration can be at habitat scale, although to be effective, larger, reach-scale projects are usually more effective. Where riffles are being restored as spawning substrates the restoration should be part of a large, network scale rehabilitation if the target species are to reach the spawning sites.

4.3.5.4 Improvement of channel diversity

Restoration of meander bends

As highland rivers become larger and shallower, rivers begin to form meander bends introducing an additional degree of diversity to the channel. Restoration of meanders at this scale can be achieved with deflectors that direct the main current from one side of the channel to the other creating associated point bars and channel deeps under excavated banks.

Deflection of the current means that in many instances banks will have to be stabilized at a desired state. This can be achieved using hard engineering solutions such as gabions, rip-rap, sheet pilings or wicker fencing, but in many instances, softer, more natural approaches using vegetation – such as trees, floating vegetation mats, biomats with stabilizing grasses on the banks or anchored dead trees can achieve the same effect.

Restoration of meander bends is usually aimed at reach or sectoral scales.

Woody debris. In smaller streams large woody debris, such as fallen tree trunks or dropped branches, creates an important source of diversity in the river. Flow variations caused by the local interruptions to flow creates deeps and shallows in much the same way as artificially placed deflectors, as well as creating small, usually short-lived impoundments within the channel. In larger rivers, logs accumulate and form large logjams, which provide similar functions to individual logs in smalls streams and help create a diversity of channels. Debris also provides habitat for certain species that are completely adapted to life in wood packs in some tropical systems.

The addition of woody debris, logjams, and other instream structures have been demonstrated to be a successful technique for improvement habitat in small and large streams. However, woody debris can causes problems in river channels for canoeists and may also be washed downstream in high flows to obstruct and endanger bridges. In these cases, anchoring or engineering of logs and other instream habitat improvement structures may be needed to protect infrastructure and boaters alike. Regardless, a certain amount of wood should be retained in the system either by artificially placing wood in the channel or by leaving natural wood that falls in place.

Woody debris is commonly restored at the habitat or reach scale though some placement of wood throughout an entire river system have recently been conducted with success.

Cover. An essential feature of highland streams is the high degree of cover afforded fish by undercut banks and erosional features in plunge pools. These are often engineered out in regulated channels and need to be restored by use of overhanging trees, logs platforms, pipes and artificially constructed overhanging banks. Provision of cover is usually habitat oriented and limited in scale.

Creation of shallows. It is often necessary to create shallows to encourage riparian vegetation in pools. This can be done by building shallow sloping areas into the bank at depths suitable for the desired vegetation. Creation of vegetated shallows should be done at the habitat or reach scale.

Maintenance or restoration of main channel deeps. Many larger rivers have deep areas that provide permanent habitat to some resident species and seasonal shelter for others. The deeps tend to become silted once the river channel is regulated and periodic dredging may be needed to restore the deeps so that they can fulfil these functions.

4.3.5.5 Protection of riparian structure

One of the major sources of problems in streams is the breakdown of bank structure through cattle grazing. Great improvements in stream stability and form can be achieved simply by fencing the river banks so that access by cattle or wildlife is impeded. A riparian fringe of trees and thickets can also achieve the same effect.

4.3.5.6 Mitigating the effects of roads

Roads and railways frequently run alongside or across highland rivers particularly in deep valleys. The presence of railways and paved and unpaved roads can have negative impacts on aquatic ecosystems including altering hydrologic regimes, increasing sediment supply to streams and constraining channels, all which influence channel and habitat characteristics and ultimately impact aquatic biota. For example, in urban areas, roads and other impervious surface areas lead to increases in peak flows, channel incision, and loss of stream complexity. Drainage from forest roads to stream channels can alter the amount and timing of water delivery to streams, as well as the delivery of sediment eroded from hill slopes or road surfaces. Roads also alter sediment supply through increased frequency of landslides and increased surface erosion. Ultimately, the changes in sediment and hydrology have a negative impact on many fishes and other aquatic biota.

The various rehabilitation actions that can be used to reduce these negative impacts can be divided into three categories: sediment reduction, restoration of hydrology, and connectivity. A variety of methods are used to reduce sediment delivery and landslides induced by roads or road construction. These include resurfacing roads, reducing traffic, increasing the number of stream crossings, stabilizing cut and fill slopes, and replacing stream crossings to improve the natural transport of sediment and biota. In addition, complete road removal or abandonment of roads, which may use many of the previously mentioned techniques, is also a common method to reduce road impacts. Actions to reduce hydrologic effects of roads in rural or forested areas include some of the same activities as sediment reduction, as well as increasing the number of cross drain structures, water bars to distribute water onto the forest floor or into existing stream channels, and other techniques to prevent the road or road ditches from serving as channel networks. In urban areas, several new techniques have been applied in recent years to control increased runoff and increase storm-water infiltration including, but not limited to, porous paving, removing hard surfaces where possible and planting with vegetation, a variety of detention, retention, or seepage basins or ponds, overflow wetlands, addition of rainwater cisterns, high-flow bypass channels, alternative drainage systems, and low-impact development for new construction.

In addition, road crossings such as bridges, pipes and culverts often are impassable to migrating fish and other biota. Bridges should also be designed to allow the free passage of fish, without introducing undue constrictions and local accelerations of flow. Culverts and pipes that represent barriers to fish migration should be removed or replaced with larger culverts or bridges that allow for fishpassage at a variety of flows (see also the section on connectivity). Adequately sized bridges and culverts should be required when approving any new projects for road and bridge building.

Guidelines – highland river channel diversity

i) ***Pools, riffles, and habitat complexity are common techniques for restoring highland river ecosystems.***

ii) ***In lower slope highland rivers, some degree of sinuosity can be introduced using flow deflectors coupled with bank protection.***

iii) ***Woody debris should be retained in the stream.***

iv) ***Adequate cover for local and migrating fish should be incorporated into the river banks.***

v) ***Shallows should be restored where needed to encourage the growth of riparian vegetation in pools.***

vi) ***Access to the river bank by cattle and wildlife should be rendered impossible or at least limited by fencing or by riparian thickets or trees.***

vii) ***Efforts must be made to mitigate for the effects of road, railway and bridge building by stabilizing banks and controlling soil loss and excessive flow, disconnecting road drainage from streams, limiting the amount of impervious road surface, and assuring that bridges and culverts allow for fish migration.***

4.3.6 Lowland rivers

4.3.6.1 Issue

Lowland rivers have been modified by a series of activities including dam building, water abstraction, river training for navigation and flood protection and separation of the river channels from floodplains and other riparian wetlands. These activities have resulted in the loss of habitat, a lessening of the river's capacity to support both resident fish and migratory species, and declines in fisheries.

4.3.6.2 Main aims

The main aims of restoration activities in lowland rivers are to:

- restore channel structure;
- restore connectivity to the floodplain;
- restore floodplain structure; and
- restore longitudinal connectivity.

4.3.6.3 The string of beads principle:

Because of the dynamics of lowland floodplain rivers, there is an overproduction of juvenile fish in years of good flooding to compensate for the mortalities during the dry season. There is often so much overproduction that in lowland reaches the river does not need to be restored or rehabilitated in its entirety but that selected sections only should suffice to maintain functioning and sustainable populations. A similar situation does not apply in upland reaches of river or in lakes, where the abundance of suitable gravel areas (riffles) determines the abundance of the species that use them for spawning.

General guideline – lowland rivers

i) ***It is not essential to rehabilitate the whole river but key areas for target species or for specific fish assemblages should be identified and rehabilitated.***

4.3.6.4 Restoration of river channels

Restoration of meanders. Meander bends are the most characteristic feature of lowland rivers. Meanders characteristically recur over about seven channel widths and may vary from low sinuosity bends to highly convoluted loops. They are characterized by a shallow point bar on their convex, inner face and an eroded deep on the concave, outer face. Meanders are often highly active migrating down channel, leaving behind them a succession of dead arms and oxbows that are incorporated into the floodplain and riparian wetlands.

Meanders may be restored or created by appropriate positioning of deflectors that accelerate natural erosional tendencies. Much depends on the placement of the deflectors because other systems can be used to narrow and deepen a wide and meandering channel, particularly to create and maintain a navigation channel.

Where channels have been modified by diversion into an artificial canal or channel, mainly in the interests of navigation or water supply, the simplest solution for restoring meander structures is to redirect the new channel into its former bed by destruction of the separating levees. This strategy only works where the original meander structure of the old bed has been maintained and not modified for agriculture or other uses.

Meander restoration is usually at the reach or sector scale. However, it only works well where the river channel can follow the natural erosion-deposition processes that cause it to migrate over the floodplain. Restoration of meander bends in rivers whose banks are protected serves little purpose.

Dual stage channels and setting back levees. Most modified lowland rivers are restricted by levees that contain the water in an artificially incised channel. This means that riparian diversity is limited and that at times of high flow there is no refuge for any fish present. These restrictions may be remedied by setting back the levees to create a two-stage channel.

Two-stage channels differ in the width of the seasonally floodable strip. This is often too narrow and serves little biological function. If sufficient space is made available between the river channel and the new levees, the channel may be allowed to meander or braid within the new confines. It also makes space available for a seasonally flooded strip that, with appropriate management, can assume many of the functions of a true floodplain. Properly managed the floodable strip may be wooded or even contain local off-channel water bodies.

Setting back levees is a large scale operation often at the sector scale using the string of beads principle. It requires riparian land to be made available and may be extremely costly.

Island creation. Islands are valuable features that increase flow variability in the channel and increase the amount of available shoreline. In wider rivers, channel islands may be created or restored. This is usually accomplished with the aid of deflectors but is especially suitable for natural approaches using trees planted on limited sand or gravel banks to initiate a process of deposition to extend the island. Island restoration is usually local at the reach scale. Rivers side channels and islands also typically recover naturally when levees are removed or restricted channels are widened or with placement of logs and log jams.

Backwaters and main channel pools. Diversity of flow and structure can be introduced into heavily engineered and featureless channels by recreating riparian roughness.

Shallow bays can be introduced into the river bank by excavation, by construction of retaining control structures or by using pre-existing natural features such as field drainage points, cattle drinking areas or confluences with small tributary streams.

Many modified rivers retain some of their old features such as relic anabranches, dead arms or backwaters created from relic channels. These should be reconnected to the channel. The way in which they are reconnected can influence the subsequent functioning of the backwater. If the reconnection is at the downstream end only, a lentic water is formed that will accommodate limnophilic fish whereas connection at both ends will create as seasonally flowing system better suited to rheophilic species. The disadvantage of lower end reconnections is that there is an increased tendency to silt up the connecting channel so periodic clearance may be necessary. In both cases, flow control structures such as submersible sills, weirs or sluices can be installed to control the characteristics of the backwater.

In some areas, natural backwater and riparian vegetation habitats can be supplemented by artificial spawning and refuge locations in the form of brush and vegetation parks. These may be installed directly along the banks of main channels, in main channel pools or in off-channel lakes and lagoons.

Backwater and main channel pool connection is usually a one-off exercise carried out at the reach scale where suitable relic features are available. As they involve extension of the wetted area of the river they usually involve acquisition of land for the purpose.

The construction of large engineered logjams composed of dozens of large logs is used to mimic natural accumulations of wood and create pool and cover in both the mainstem and sidechannels.

Guidelines – lowland river channels

i) ***Restoring river meanders only works where erosion-deposition processes in the river can operate freely***

ii) ***Where rivers channels are constricted by levees, the levees should be set back to allow the river space to flood and create diverse riparian structure.***

iii) ***Where appropriate, islands can be created in the main channel to increase diversity.***

iv) ***Relic features such as backwaters and dead arms should be reconnected to the channel to provide shelter, nursery and feeding habitat for fish.***

4.3.6.5 Restoration of floodplains

Floodplains should be regarded as integral parts of the river system. They are extensions of the river that have developed to accommodate the higher flows of the hydrograph. Thus, the dependency to separate river channels from their floodplain for agriculture or urban occupation results in fundamental disturbances to the river and to the fish within it. In particular, the close connection between the area of floodplain flooded in any one year and the commercial catch of food fish in the same or subsequent years indicates the importance of continuing to flood the maximum area of plain possible.

Floodplains usually consist of a large expanse of flat land that is flooded seasonally. Originally, many floodplains were forested but the degree of woodland has been reduced in many areas to almost nil by human activities. Many savannah plains are now covered in flood tolerant grasses and other vegetation that form floating meadows during the floods. The plain is used by wildlife, for cattle grazing and increasingly for intensive agriculture ranging from drawdown cultivation to sophisticated irrigated systems such as rice-culture. A number of permanent or seasonal lakes and lagoons are usually interspersed over the plain. These are formed by various river processes and include oxbows and abandoned channels as well as scour lakes of various types that are shallower but more extensive.

There are two main aspects to the restoration of floodplains:

- restoring seasonal floodplain and
- restoring floodplain waterbodies.

Seasonal floodplain. Disconnection of the floodplain from river channels occurs when the plain is physically separated from the channels by levees, when the channel becomes so deeply incised that water levels do not pass bankfull under normal discharge regimes or when water abstractions are such that flooding can no longer occur. The main problem with floodplain restoration is the failure of lateral connectivity and this must be restored so that flooding can be resumed.

The simplest approach to reconnection is the local removal of levees so water can flow out onto the plain. As some floodplains are very extensive and may overlap with socially sensitive areas such as farms or housing, new levees may have to be constructed at the limits of the restored area.

If the channels have become so incised as to not permit water to overbank, adjustments of level in the main channel may be made using submersible dykes that direct the water laterally over certain flows. It may also be necessary to install lateral dykes across the floodplain to direct and retain water on the plain. Alternatively, localized restorations have taken place by scraping the topsoil from the floodplain to lower areas so that they can be flooded.

Water abstractions and releases from dams must be regulated to secure adequate flows in the river at appropriate times to flood lateral wetlands.

Rehabilitation of seasonal floodplains also rehabilitates any floodplain water bodies that are present in the target area.

Care should be taken to rehabilitate the dry season phase of seasonal floodplains. For instance, overgrazing or practices that harm the vegetation should be avoided. Likewise, floodplain woodlands can add much to the diversity of habitat available.

Floodplain restoration is usually carried out at the reach or sector scale.

Floodplain waterbodies. Where it is not possible or desirable to rehabilitate seasonal floodplain it may still be possible to rehabilitate some of the permanent waterbodies should any remain as isolated lakes or wetlands. This can be done by opening a connecting canal from the river. Flow through the canal may be controlled by submersible dykes, weirs or sluices (see section on connectivity for further observations). Connected canals have a tendency to silt-up, especially if flow is controlled and therefore, periodic dredging may be necessary. If the floodplain water body risks flooding the seasonal plain at high water, some restrictions on inflow may be appropriate. Alternatively, the water body and connecting channel may be enclosed in a levee.

In some floodplains water is retained in the floodplain water body for longer than would naturally be the case in order to increase productivity. Production can be further enhanced by stocking or feeding the retained fish.

Should no relic water bodies exist, new bodies may be made artificially. Shallow floodplain lakes have been created by excavating depressions on the floodplain called scrapes. Alternatively, ponds and lakes created for other purposes, such as gravel extraction, or borrow pits for road embankments or housing, may be incorporated into the river–floodplain systems. In such cases the form of the lake may be tailor-made to the needs of the local fish community and such landscaping can be specified as a condition of the extraction licence.

Excavation of new waterbodies on the floodplain is common practice in some areas either associated with rice-culture or for reclamation of wetlands for agriculture. In both cases the ponds can support self-stocking species that spread out over the seasonal floodplain or rice field to feed during the flooded phase. Drain-in ponds of this type may be stocked and fed to improve production thus incorporating them into extensive aquaculture systems.

Guidelines – floodplains

i) ***Seasonal floodplains may be restored by locally opening levees to allow water to freely flood the plain. New levees may have to be installed away from the river channel to contain the area flooded.***

ii) ***Where rivers channels are so deeply incised as to prevent flooding, submersible weirs may need to be installed in the river channel to raise water levels to exceed bankfull.***

iii) ***Dykes may need to be constructed to slow water flow and keep the floodplain flooded for as long as possible.***

iv) ***Care should be taken to conserve floodplain vegetation, especially floodplain woodlands.***

v) ***Existing relic floodplain waterbodies or features such as gravel extraction ponds and borrow pits should be connected to the main channel by suitable channels. Levees may need to be realigned to control the extent of flooding of such water bodies.***

vi) ***New water bodies can be created by excavating suitable depressions in the floodplain. These include features such as drain-in ponds or rice-fish ponds expressly created to support fisheries.***

4.3.7 Estuaries and coastal wetlands

4.3.7.1 Morphology

Estuaries are the last part of the river before it enters the sea. As such they represent a transition between purely freshwater conditions of the river and the marine conditions of the sea. The form of the estuary is linked to the amount of silt carried down the river as well as the underlying geomorphology, energy environment (wave exposure) and coastal drift, etc. Heavily silted rivers form complex deltas whereby the river discharges through many channels (distributaries). Less heavily silted rivers discharge through a simple channel. Coastal wetlands and lagoons are frequently associated with rivers as they discharge to the sea. These are normally formed by longitudinal currents along the coastline that block the estuary allowing it to form a natural impoundment separated from the sea by a mud or sand spit.

As a result of the sedimentation, morphological and energy processes estuaries and coastal wetlands include areas of low lying floodplain and salt marsh that are subject both to the seasonal freshwater flooding by the river and the twice daily tides. The coastal floodplain is vegetated by a characteristic succession of species determined by frequency of flooding and salinity. This ranges from mud, through emergent grasses and associated species to a covering of characteristic vegetation that culminates in mangrove forests in tropical and equatorial regions.

The transitional nature of the estuary is dominated by the interplay between fresh and saline water that produces a daily and annual fluctuation in the water level, and the temperature, turbidity and salinity of the water that is present. Saline waters may penetrate for great distances upstream, flowing along the bottom of the river as a saline tongue in seasons of low freshwater flow. Tidal influences may also be felt far upstream even though the rising and falling water is fresh.

4.3.7.2 Fisheries ecology of estuaries and coastal wetlands

Estuaries are rich and productive places but they are also dynamic and stressful. It is particularly difficult for many organisms to tolerate salinity and temperature stress at the same time. The biota present in estuarine areas is adapted to these stresses in a number of ways. In the case of fish, coastal lagoons and estuaries are occupied by three main blocks of species.

- Stenohaline freshwater species that move into the estuary from the inflowing rivers during rainy and flood seasons to feed when the water is mainly fresh to slightly brackish. During periods of low flow these species withdraw into the rivers and are replaced by marine species.
- Stenohaline marine species migrate in from the sea, often to reproduce during dry seasons when the water is primarily saline. Coastal wetlands are particularly important spawning and nursery sites for many marine species.
- Euryhaline species that are permanently resident in the transitional zone of the estuary or coastal lagoon being adapted to the fluctuating salt concentrations. Some species have a larval phase that remains in the lagoon for at least one freshwater season.

4.3.7.3 Flow

Flow plays an especially important part in regulating estuarine and lagoon productivities because of fluctuations in imported nutrients and organic matter, as well as salinity. Interruptions to flow by water abstraction and damming can affect the estuarine ecosystem in three ways:

i) By interfering with the erosion deposition cycles in the river it can alter the amount of silt deposited in the deltaic region. Many deltas and coastal lagoons today are threatened with disappearance because the deposition of new silt by the river is less than the erosion of deposited silt by the seas.

ii) By changing the seasonal discharge of nutrients, organic matter and transported organisms it can alter the productivity characteristics of the estuarine and coastal wetland system.

iii) By interfering with the quantity and timing of discharge flow regulation can impact on the quantity and composition of the species that are present at any point in the transition from fresh to saline waters. Changes to the hydrograph can also change the pattern of flooding of the lateral floodplains in a similar manner to lowland rivers.

4.3.7.4 Measures for the rehabilitation of estuaries and coastal lagoon

Many of the rehabilitation methods that can be used in lowland rivers apply to the estuarine portion insofar as it is an extension of the lowland river channels and their associated floodplains and wetlands. There are, however, a number of issues peculiar to the estuarine and coastal zone that require specific solutions.

Issue. Current management of rivers and the coastal zone is impacting on the structure and functioning of estuaries and associated lagoons and coastal wetlands. Changes to silt loads are diminishing the rate at which coastal areas are renewed, leading to their degradation and disappearance. Changes to water discharge patterns are leading to changes in salinity patterns. Changes to the coast itself by urbanisation, deforestation, mangrove removal for aquaculture, beach control and port construction are leading to changes in erosion patterns. All these influence the composition and abundance of fish in these highly productive environments.

Aims. The main aims of rehabilitation on estuaries and associated wetlands are to:

i) maintain or restore the tidal regime, salinity balance and nutrient inputs in the estuary;
ii) to prevent erosion of the estuary by controlling silt levels in the river;
iii) to restore vegetation and in particular mangrove forests.

Flow. The flow requirements for maintaining a salinity regime appropriate to the local fauna in the estuary should be expressly included in any environmental flow regulation for the river or rivers feeding estuaries, deltas and coastal wetlands. Sufficient flows both from the river and from the sea should also be provided for the timely inundation of wetlands associated with estuaries.

At the same time, cross river coastal barrages and control structures should allow for the entry of natural delivery of adequate quantities of marine water as to conserve the salinity levels needed for the seasonal penetration by stenohaline marine species and for the maintenance of euryhaline residents.

Similar considerations to those in the section on environmental flows apply for semi-migrant and migrant anadromous and catadromous fishes resident or associated with estuaries and coastal wetlands.

Sediment loads. On the large scale, river basin management should aim to maintain the levels of sediment load needed to maintain coastal deltas and wetlands. This includes land use practices as well as the design of dams and weirs so as to release sediment for transmission downstream.

Connectivity. Connectivity is required both to the sea to facilitate entry by marine species and to the inflowing rivers to allow for the free movement of stenohaline freshwater species and anadromous species up and down river. This means that any marine barrages should have opening regimes appropriate to local fish species and that any riverine barrages should be equipped with fishpassage facilities.

Control of coastal habitat. Legislation should be in place to control the conversion of essential salt marsh and removal of mangrove vegetation especially for coastal aquaculture. Projects for construction of sea walls for prevention of flooding or drainage for agriculture and urban development should be subject to careful environmental impact assessments. Where possible, salt marsh and mangrove ecosystems should be restored by removal of any sea walls that have been used for reclamation of coastal wetlands for agriculture and urbanisation or by designating such areas as protected. Abandoned shrimp culture or coastal agricultural sites should be reforested.

Guidelines – coastal and estuarine

i) ***Water abstractions and controlled flow regimes should be regulated so as to conserve natural salinity regimes, tidal inundation, temperatures and nutrient inputs in estuaries and estuarine wetlands.***

ii) ***River basins should be managed to ensure that sufficient silt reaches the sea as to conserve the area of coastal deltas and wetlands.***

iii) ***Connectivity should be maintained or re-established with both the inflowing rivers and the sea.***

iv) ***The natural vegetation succession on coastal wetlands should be preserved or restored. In particular, measures should be adopted to conserve mangrove resources.***

4.3.8 Connectivity

4.3.8.1 Issue

Rivers throughout the world have become fragmented by dams and weirs and other river control structures. Such structures interrupt the connectivity of the river and with it fish migration. As a result, migratory fish species have been eliminated from many river systems and are under increasing pressure in others.

4.3.8.2 Aims

To provide free passage for fish and other aquatic migrants (e.g. shrimps, crabs, river dolphins, macrozoobenthos) up and down the main channels of rivers and laterally between floodplains and river channels.

4.3.8.3 Longitudinal connectivity (upstream/downstream)

Restoration of longitudinal connectivity is usually regarded as the priority measure in river rehabilitation. Removal of obstacles to migration can restore both upstream and downstream passage as well as habitat. Construction of fishpasses for upstream passage and bypasses for downstream passage are accepted mitigation measures. However, plans for removal of obstructions or for construction of fishpassage facilities should be subject to prevailing habitat conditions upstream and/or wider planning at river basin level. Restoring a migratory pathway should only be done if the upstream conditions are suitable for the target species, or might become suitable in a reasonable timeframe.

Safe downstream passage of fish needs to be considered carefully as mortality resulting from passage through hydraulic turbines or over spillways can be significant. Experience shows that problems associated with downstream migration can be a major factor affecting anadromous or catadromous fish. This is especially significant for species with individuals of great body length.

Removal of obstacles. The best way, and an increasingly popular one, to re-establish longitudinal connectivity is to decommission (i.e. remove) dams, barrages, weirs or other obstacles. This option is gaining increasing importance in North America and Europe when obstacles have ceased serving their original purpose, when licences have expired, when repairing and retrofitting with fishpassage facilities is economically not viable, where the dam owners no longer have an interest in the structure, or where ecological aspects are put above economic considerations. The simple removal of the structure may restore the original condition of the river in the long term. There might, however, be some problems as usually reservoirs created by dams accumulate silt that may alter the erosion/deposition characteristics of the river downstream for some years after the removal of the obstacle. There also may be accumulated contaminated sediments, particularly in the case of rivers where mining is practised. In these cases, precautions have to be taken that public and ecological health is not affected.

Should decommissioning not be possible, mitigation has to be sought.

Fish passage facilities. Two aspects of migration up and down the main channel are important: active upstream and/or downstream migration of adult fish or juveniles, and downstream movements of eggs, larvae or juveniles either through active migration or drift.

Depending on the behavioural characteristics and swimming performance of individual species, even low obstacles can interrupt upstream migration. Some fish are strong swimmers and can, to a certain extent, leap over obstacles. Others are less vigorous swimmers that tend to use the slacker water close to the bottom to move against the current and are easily impeded by relatively low obstructions. This implies that either fishpasses are constructed for specific target species only or that they are designed in such a way as to facilitate movement of all species present. Most of the earlier designs of fishpass were directed at salmonid fishes that swim strongly and can, to a certain extent, leap over obstacles but these designs haven't proved a success for many other groups of species. Therefore, the design of each fishpassage facility must be adapted to the local species present. Recently developments have concentrated on more versatile types of pass, such as the vertical slot pass, that are suitable for a greater range of fish and invertebrate species.

One of the major challenges with all types of fishpass is inducing the fish to find and enter the fishpass entrance. Much depends on the ratio between the outflow from the pass, the background discharge from the dam and the turbine discharge, and the possibility for fish to notice the attraction flow. An increasingly common practice is to improve the attraction flow by adding discharge into the lower part of the fishpass, close to the fish entrance. This additional water can be sent through a small turbine to dissipate its energy which makes the measure more tolerable economically.

The velocities and turbulence conditions must be adapted to the capacities of the target species. The dimensions of a pass must be chosen in relation to the body size of the biggest individuals that are expected to occur. Each fishpass must be designed in such a way as to function satisfactorily under varying flow conditions, within reasonable limits. These flow conditions must be considered in assessments of environmental flows.

The accepted downstream passage technologies to exclude fish from swimming through turbines are physical screens, angled bar racks and louvers associated with surface bypasses. Problems associated with behavioural guidance devices have not yet been satisfactorily solved for a wide range of conditions.

Installation and operation of fishpassage facilities should bear in mind the interests of other users. For example, it is possible to construct modern fishpasses that allow the downstream passage of canoes and other craft. Fishpass design and installation is critical and should be referred to fully qualified experts (see for example Larinier, 1992 a,b,c,d and FAO/DVWK, 2002 for detailed discussions of construction and installation of various types of fishpass).

All fishpasses need regular maintenance to clear accumulated trash and ensure that flow is not obstructed.

Various types of pass are available and distinguished distinction is made between nature-like passes and more technical solutions:

Nature-like passes

Fish ramps. Fish ramps are hard engineered structures where natural materials such as boulders are used to create slopes that allow a great variety of fish and invertebrates to ascend or descend the river. However, the use of ramps is generally limited to low obstacles. Strategic placement of boulders can direct currents and provide shelter for fish as they ascend the structure. As in other fishpasses, the velocities and turbulence conditions on the ramp must be adapted to target species. The width of the structure and its generally low slope means also that downstream migrants have a good chance of survival. Ramps have numerous advantages in that they are more aesthetically appealing, they provide a varied series of habitat conditions and can be placed into the main channel of the river with no or little requirement for extra land. Being constructed in the main channel, fish have little difficulty in finding the entrance. However, maintenance requirements are also relatively high as fish ramps are also susceptible to clogging.

Bypass channels. Bypass channels are long channels around obstacles that begin downstream of an obstruction and end far enough from the turbine intake in, or upstream of the reservoir. They have the advantages of blending well into the landscape and providing new habitat for a variety of species. They can be passed upstream and downstream by a large variety of fish. Unfortunately, bypass channels usually require a large amount of land and are often expensive to install. However, if space permits, they may be easily retrofitted to existing dams and obstructions because they do not touch the existing dam structure. They are also very sensitive to fluctuations in water levels (headwater and downstream) and sometimes have to be connected to the river by technical sections at the upper and lower ends. As for all passes, the entrance has to be in an optimal position for fish to find it without problem. They have a reduced tendency to clogging thereby lowering the cost of maintenance.

Technical fishpasses

Pool-type passes and baffle passes. Technical fishpasses are hard engineered structures usually of the pool-and-weir, pool, or baffle type intended primarily to assist fish in migrating upstream. Many different designs are available with different types of cross walls and pool dimensions. The design (i.e. pool size and drop between pools) must be adapted to the swimming capacities of the target species. Pool-and-weir passes are one of the oldest designs and have proved their value for strong swimming species as well as some bottom migrating species (if there are bottom orifices or slots and if good maintenance is done). Depending on the design (especially the size of the openings), their flow requirements can be relatively low but they require high maintenance as the orifices and slots in the cross walls are especially prone to clogging. A special type of pool-and-weir pass is the vertical slot pass which proved efficient for many different species. Vertical slot passes may have higher flow requirements as a function of the slot size. Baffle-type passes, e.g. the Denil pass, have the advantage that they can be used on relatively steep slopes and thus require limited space. They are more easily retrofitted to dams lacking fishpasses than the pool-type passes but they can be used by a smaller range of species because they are more selective due to the particular flow conditions. An advantage is that they do not need high discharges. They have disadvantages in that they are intolerant of variations in headwater level and they are easily disturbed by clogging with debris requiring high maintenance.

Alternative solutions

Several alternative solutions have been used for enabling passage of fish upstream. This include large mechanisms like fish lifts and fish locks that have the advantage that they can operate over considerable differences in height and can thus accommodate the needs of high dams. Both fish lifts and locks are usually operated at intervals, and locks especially may not be open continuously. Their capacity to move large quantities of fish at once is limited. In some cases, fish are captured and transported around the dam by truck for release either upstream or downstream. These specialized approaches are usually applied where particular conditions exist or where there is a particularly valuable local resource.

The new concept of installing an additional turbine, to dissipate the energy of the additional water added to create a better attraction flow, is increasingly used in connection with technical passes.

In some countries, the use of ship locks for passing fish is being successfully explored.

Fishpass monitoring is very important to ascertain that the passage facility functions well (or, if not, to suggest improvement), to allow predictions of potential fish population development upstream or downstream and to design management measures (Travade and Larinier, 2002). Monitoring effectiveness or efficiency are two different concepts (Larinier, 2001). Effectiveness of a fishpass 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, i.e. visual inspection, trapping, video checks. The efficiency of a fishpass 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 fishpass 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 fishpasses and the cumulative effect of various dams along a migration path.

Bridges and culverts. Bridges and culverts may cause problems for migrating fish, particularly in that the restriction of the channel may concentrate flow to the point that fish can no longer proceed upstream. Adequate provision should be made for fishpassage through such structures or the structures removed or replaced with a structure that allows for fishpassage at a variety of flows.

4.3.8.4 Lateral connectivity (between channel and floodplain)

Lateral connectivity between river channels, and floodplains with their waterbodies and wetlands should be maintained to allow water to seasonally flood the plain and to allow access by fish. Several examples have been given above as to how this may be achieved by the removal and setting back of levees and regulated by sluices and weirs.

Floodplains are often crossed by roads and railway embankments. These can fragment connectivity, hindering the free movement of water and fish. To prevent this, embankments should have adequate provision for fishpassage in the form of culverts and underpass bridges [see also section on Roads under Highland rivers.

Enclosure of portions of the floodplain by a series of levees to form polders is increasingly common in tropical floodplains. The polders are pierced by sluices that allow for greater control of water inflows and outflows in the enclosed area, mainly with the goal of increasing agricultural production. However, opening and closing regimes in the interest of crops frequently disadvantage fish, although the sluices can also be operated to improve fish production.

4.3.8.5 Vertical connectivity

Vertical connectivity is important in many rivers as ground water inflows form a significant input to many small streams and marginal wetlands on floodplains. Filtration from surface waters of river channels and wetlands also recharges aquifers and ground water for later release into the river. Vertical connectivity also permits water to flow through and clean riffles. Care should be taken to preserve vertical connectivity by not using hard engineering to replace channel bottoms or floodplain surfaces with concrete.

Guidelines – connectivity

- ***i)*** ***Longitudinal connectivity should be restored as a matter of priority by removing obstacles or installing appropriate types of fishpasses at obstructions. The design has to be adapted to the capacities and the behaviour of the target species. Natural-type structures are to be preferred where possible.***
- ***ii)*** ***Plans for removal of obstructions to migration or for the construction of fishpasses should, however, be subject to wider planning at river basin level.***
- ***iii)*** ***If an obstruction such as a dam or weir no longer serves a purpose, preference should be given to its removal.***
- ***iv)*** ***Bridges and culverts to facilitate flow of water down streams or across floodplains should be so designed as to present the least obstruction possible to fish movements.***
- ***v)*** ***Lateral connectivity should be restored by removal or local piercing of levees. This may require set back of levees to contain flooding and flows can also be controlled with sluices, weirs or submersible dykes.***
- ***vi)*** ***Access for fish to agricultural polders should be guaranteed by correct operation of the water control mechanism.***

4.4 Lakes and reservoirs

4.4.1 Morphology of lakes and reservoirs

Many systems have been used to classify lakes according to their origin, form and function. Three major factors determine the nature of lakes, the ways in which they respond to human induced changes and their needs for rehabilitation.

4.4.1.1 Trophic state

The amount of nutrients present in a lake (trophic status) determines the oxygen balance of the lake, the transparency of the water, the types of phyto- and zooplankton present and the nature of the fish community. Five trophic states are generally recognized: oligo-, meso-, eu-, hyper-, and dystrophy. Addition of nutrients over and above natural levels can change a lake from one trophic category to another with accompanying changes in planktonic, invertebrate and fish communities. This process, known as “eutrophication”, is in principle reversible, though often difficult in reality.

4.4.1.2 Depth

Lakes are classified by depth because the shallowest waters are the most productive and the proportion of shallow water to deep waters is important in determining the overall productivity of the lake.

Deep lakes usually stratify as the temperature of the deeper waters drops relative to the surface waters. This forms a separation between the two masses of water known as “stratification” with a cold, deep, deoxygenated and nutrient rich hypolimnion underlying a warm, well oxygenated and nutrient poor epilimnion. In eutrophic lakes the deep, cold waters become de-oxygenated and cannot support fish. In lakes where there is a seasonal drop in temperature accompanied by storms, the two masses of water become remixed with a redistribution of nutrients and re-oxygenation of the bottom waters. Lakes may be classified according to the frequency with which this occurs (mono-mictic, mero-mictic).

4.4.1.3 Shoreline development

Because shallower waters are more productive, the relationship of shoreline length to area is an important feature influencing lake productivity. Many types of natural lakes tend to have relatively simple shorelines but reservoirs, or lakes formed from natural dams, usually have long convoluted shorelines with numerous arms and sometimes shallow bays.

4.4.2 Fisheries ecology of lakes and reservoirs

The number of fish species supported by lakes depends on latitude and age. Arctic and cold temperate lakes support very few species but lakes in the tropics support large numbers of species, often with a high degree of endemicity.

Lake fish faunas can be classified into a number of groups depending where they live in the system (Annex VI). Many species are highly mobile within the system, migrating to and from different spawning, nursery and feeding habitats within the lake and the inflowing brooks or rivers. Reservoir faunas are derived mainly from the original river fauna but are frequently modified by the introduction of exotic pelagic and lacustrine fishes. They are often stratified based on the degree of freedom of movement of fish into the inflowing tributaries of the former river system. Thus, in addition to the broad general categories listed in Annex VI, reservoirs can be divided into three main areas:

- A riverine portion at the upstream end where many of the original riverine species can continue to survive.
- A middle section with a lacustrine fauna based on such river species as have been able to adapt to the new impounded conditions together with any species introduced to enhance the fishery.
- A lower section near the dam wall that is the deepest and often stratified.

4.4.3 Measures for the rehabilitation of lakes and reservoirs

4.4.3.1 Issue

The ecological status of lakes throughout the world is under threat from a number of human induced processes. Nutrient levels in many lakes are rising in response to discharges of residential and industrial wastes and diffuse infiltration from agricultural fertilizers. Lakes are also subject to toxic pollution, thermal pollution, and acidification. Lakes and reservoirs are being dewatered by abstractions from inflowing rivers or from the lakes themselves and the resulting water level fluctuations are critical, especially in reservoirs. Sedimentation rates are often higher than natural background levels due to changes in land use. The nature of shorelines is also being altered by agriculture, deforestation, urbanisation and human occupancy.

4.4.3.2 Aims

The main aims of lake rehabilitation are:

i) To restore a healthy nutrient balance in lakes that is as close to the historical trophic character of the waterbody and to the needs of the fish fauna associated with it as is feasible.
ii) To extend the life of the lake or reservoir by controlling sedimentation and flow.
iii) To reintroduce diversity of riparian habitat.
iv) To improve water quality including control of eutrophication, accumulation of toxic pollutants such as include heavy metals and PCBs, and the neutralisation of acid conditions.

4.4.3.3 Water quality

Eutrophication. Eutrophication is the major problem facing lakes worldwide. Urbanisation and intensification of agriculture within lake basins has generally resulted in increases in nutrient levels with a consequent decline in water quality. This problem must be rectified before any other rehabilitation initiatives are undertaken, or at least at the same time. Guidelines for the control of eutrophication of aquatic systems are given in general in section. The following additional specific actions may be followed to improve nutrient levels in lakes.

Hypolimnetic drains

Nutrient-rich water is piped by gravity flow from the hypolimnion, preferably from the deepest point of the lake, into the lake outlet. A small weir may be needed to create a difference in water level between the lake and the outlet. Bottom outlets in reservoirs may fulfil a similar function. Hypolimnetic drains are quite effective in smaller lakes but the discharge of cold, and sometimes anoxic, water into the river downstream may create problems.

Lake aeration and oxygenation

Lake aeration systems are particularly effective in small lakes or bays of larger ones. While generally successful on a local scale, aeration is costly and temporary. It is only advocated, therefore, in the restricted circumstances of ornamental lakes, lakes of major importance to recreational fisheries and enhanced systems associated with extensive aquaculture.

Acidification. Oligotrophic lakes of the cool temperate and sub-arctic regions are often acidified by wash-out of atmospheric contaminants through acid rain, resulting from industrial activities. The acidification may become so severe as to eliminate all aquatic life. Two approaches to resolve this problem have been adopted. Firstly, a general restoration policy to clean-up emissions from industry and power generation has been implemented in most countries. This goes beyond fisheries in that other sectors of the economy such as forestry and agriculture are also affected by acid rain. Furthermore, degradation of aquatic environments arising from air pollution requires concerted international and national action to address it. Secondly, mitigation of the acidification is carried out by systematic liming of the lakes. This solution has proved successful on a local scale and for a limited time so repeated applications of lime are needed to maintain water quality.

4.4.3.4 Flow

Lakes and reservoirs usually form integral parts of river systems. As such they are subject to changes in natural flow regimes resulting from water abstractions and damming.

Inflow and outflow regimes. Lakes and reservoirs depend on a balance between flow into the lake from tributary rivers and groundwater, outflow to rivers downstream and losses through seepage to maintain their level. In extreme cases, insufficient inflow will result in the lake getting smaller or even disappearing completely. It is, therefore, necessary to allocate sufficient water within the basin for the lake’s continued existence. This is a basin management problem that goes far beyond fisheries but in which fisheries should have a say if the lake harbours fishery resources.

Drawdown. Reservoirs, and lakes where large scale abstractions occur, may suffer from overly rapid fluctuations in water level. Over-rapid rises in level can affect spawning fish adversely as rocky spawning substrates, vegetation or nests can be submerged to excessive depths in a very short time span. Similarly, over-rapid falls in level can result in stranding of eggs, nests or fish in exposed riparian habitats. Water management regimes should be adopted that correspond to the needs of the fish in the reservoir.

Productivity. In some river-dependent lakes and reservoirs the productivity of the water body and the resulting fish yield depends on seasonal injections of nutrients carried by inflowing waters. Flow regimes in inflowing rivers should take this into account.

Inflowing rivers. Many species in lakes and reservoirs depend on inflowing rivers for spawning. They can only use these environments if conditions are appropriate for migration and spawning upstream. Similar considerations to those in the section on environmental flows apply here. See also section below on connectivity.

4.4.3.5 Sediment

One of the major problems affecting lakes and reservoirs is sedimentation. Ageing of lakes through filling in with sediment is a natural process, but this process can be accelerated in areas where land use patterns within the basin artificially increase sediment loads. For this reason many reservoirs have a shorter useful life than originally designed.

Build up of sediment can be combated mainly through improved land-use practices in the basin upstream. As such, this is a basin planning problem that goes beyond fisheries in its scope and importance but it is important that fishery managers be heard and can contribute to basin planning. Local solutions, especially in small dams, involve dredging and either tipping the spoil into the out-flowing river or onto the land adjacent to the reservoir.

Local sedimentation, especially in the upper part of reservoirs, can be beneficial in that it increases habitat diversity by introducing riverine wetland thus providing habitat for many riverine spawning species.

4.4.3.6 Connectivity

Connectivity to tributaries. Some lake species migrate to rivers to spawn and to use upriver areas as nursery sites. Connectivity between the lake and its tributary rivers must be maintained over a sufficient distance for the fish to perform these functions. This means that in inflowing rivers that are fragmented by dams and weirs, appropriate structures be installed to allow for fishpassage (see section on longitudinal connectivity P.

Connectivity to downstream river. Lakes should also be connected to the river downstream to facilitate upstream and downstream migration by fish. Where the outlet of the lake is blocked by a dam or weir, or at reservoirs where connectivity is interrupted, an appropriate type of fishpass should be installed for both upstream and downstream migration. In the case of rivers with reservoir cascades, mechanisms for upstream and downstream migration must be particularly efficient because otherwise fish moving upstream might be delayed excessively (and not reach the target habitat in time) and cumulative losses of fish moving downstream through successive dams will add up to intolerable numbers, leaving few fish to reach the lower parts of the system.

Connectivity to riparian wetlands and lagoons. Lateral connectivity between a lake or reservoir and any associated wetlands may be very important for species that use such areas as breeding or nursery habitats.

4.4.3.7 Riparian restoration

Shoreline state. The littoral zone is the most productive in most lakes and plays an essential role in the breeding and rearing of young in many species. There is an increasing tendency for human occupancy and use to modify lake shore for urbanisation, recreational facilities such as marinas and holiday cottages or farms. In addition, major communication routes, roads and railways occupy lake shore requiring protective concrete walls, gabions or rip-rap.

The shorelines of some lakes are extremely diverse with successions of sandy beaches, gravel spits and reefs and rocky reefs. Much of the diversity of species found in lakes arises from specific adaptations to these habitats. Where such diversity has been destroyed, every effort should be made to restore affected zones. Usually this involves the artificial restoration of reefs and barriers.

Vegetation in lakes. Vegetation along the shorelines of lakes tends to be removed by human occupation and use. Vegetation fulfils many valuable functions (see the general section on Vegetation) and its removal can result in destabilization of the shoreline, increased inputs of eutrophicating nutrients, lack of shelter and nursery areas for fish etc. Restoration of submersed, emergent and floating vegetation as well as riparian woodlands is a priority for shoreline rehabilitation.

Restoration of vegetation should be properly planned on the basis of background data on the historical state of the target area. Information is needed about the nature and extent of water level fluctuations, and on plant species that are suitable for transplanting and already belong to the natural flora of the area.

Spawning areas. Spawning areas tend to disappear as the shoreline is stabilized and the lake is separated from lateral riparian wetlands. Two major spawning habitats are most affected: gravel beaches for lithophilic spawners and vegetated wetlands for phytophils. Removal of bank protection and armouring is the most direct way to rehabilitate these areas. Several mechanisms have been adopted to rehabilitate spawning habitats of shorelines where it is not possible to remove bank protection including:

Creation of new spawning gravels. New spawning gravels may be constructed artificially by physical replacement of the missing substrate as beaches or gravel bars.

Excavated side channels. Artificial side channels may be excavated into the shoreline to increase the area of shallow water for nursery and spawning habitat for fish and water fowl.

Reconnection of riparian wetlands. Where riparian wetlands have been separated from the body of the lake, or filled in for agriculture these should be reconnected or restored using methodologies similar to those used for floodplain rehabilitation. Where appropriate, brush parks installed in shallows of the main lake or in adjacent, connected waterbodies can be used for the same purpose.

Artificial spawning beds. Artificial and temporary structures can be placed in lakes and reservoirs to encourage fish to breed and seek refuge: These include brush parks and floating enclosures containing twigs, mosses or artificial material.

Cover structure. Where natural accumulations of logs and other cover have been removed the placement of logs, brush and other natural or artificial cover structures can be useful for creating fish cover and spawning habitat.

Guidelines – lakes and reservoirs

i) Water quality should be controlled consistent with the historical trophic state of the lake or reservoir and the needs of its fish population. Acidified lakes should be limed to maintain pH within a tolerable range.

ii) Flows should be adjusted at basin level to ensure the continuing existence of the lake, to maintain its productivity and to correspond to the needs of migratory elements of the fish fauna.

iii) Sediment quantities should be controlled at basin level by adoption of appropriate land-use practices.

iv) Connectivity should be maintained with inflowing and out flowing rivers so that migratory fish can continue to move upstream and downstream to satisfy the particular physiological needs compulsory to complete their lifecycle successfully.

v) Damaged shorelines should be rehabilitated by re-vegetation, restoration of spawning substrates and improvement in shoreline diversity.

5. MONITORING

5.1 Issue

Monitoring[3] and evaluation of rehabilitation efforts is critical for determining the effectiveness of actions aimed at improving habitat and increasing fish and biota numbers or conditions. Unfortunately, few projects are monitored or evaluated properly and little adequate information exists on the effectiveness of most rehabilitation techniques. A properly designed and implemented monitoring and evaluation programme is a necessary and critical component of any rehabilitation activity and should be incorporated into initial project design.

5.1.1 Types of monitoring

The evaluation of rehabilitation activities is often called effectiveness monitoring as it is concerned with determining the physical and biological effectiveness of individual or various rehabilitation actions. There are a number of other types of monitoring including baseline, status and trend, and implementation monitoring, which provide important information for designing rehabilitation projects. Here we will focus on the steps for effectiveness monitoring (for a thorough review see Roni *et al.*, 2005).

5.1.2 Steps for developing a monitoring programme

Several logical steps should be taken when designing any monitoring and evaluation programme. These include establishing project goals and objectives, defining clear hypotheses, selecting the monitoring design, monitoring parameters, spatial and temporal replication, and parameter sampling scheme. The final two steps include implementing the programme and analyzing the data collected and communicating results (Figure 3). Many of these steps are interrelated and should occur simultaneously. For example, monitoring design depends on hypotheses and spatial scale, just as the number of sites or years to monitor depends in part on the parameters selected.

5.1.2.1 Define objectives and hypotheses

Determining the objectives of the project and defining key questions and hypotheses are the first steps in developing a monitoring programme (Table 7). Defining the key questions depends on the overall rehabilitation project objectives. Evaluation of rehabilitation activities can be broken down into four major questions based on scale (e.g. site, reach, and

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[3] Systematically checking or scrutinizing something for the purpose of collecting specific categories of data, especially on a recurring basis. In ecology, it generally refers to systematically sampling something in an effort to detect or evaluate a change or lack of change in a physical, a chemical, or a biological parameter.

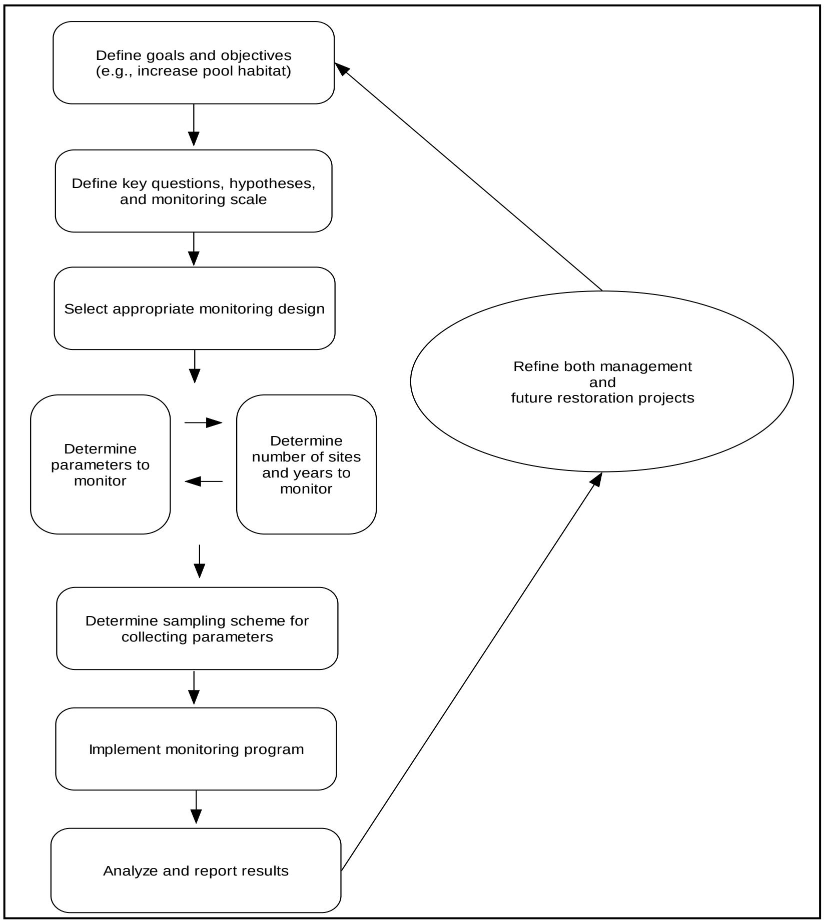

Figure 3. Flow chart of steps to be taken in designing monitoring and evaluation programmes for rehabilitation projects. From Roni *et al.* 2005.

watershed) and desired level of inference (number of projects). These include evaluations of single or multiple reach-level projects and single watershed or multiple watershed-level projects. For example, if one is interested in whether an individual rehabilitation action affects local conditions or abundance (reach scale), the key question would be: What is the effect of rehabilitation project x on local physical and biological conditions? In contrast, if one is interested in whether a suite of different project types has a cumulative effect at the watershed scale, then the key question would be: What is the effect of this specific rehabilitation project on local physical and biological conditions? While some actions such as riparian plantings or instream wood placement can cover multiple adjacent reaches or occur in patches throughout a geomorphologically distinct reach, the initial question is still whether one is interested in examining local (site or reach scale) or watershed-level effects on physical habitat and biota.

Table 7. Overarching hypotheses for monitoring aquatic rehabilitation divided by scale and number of projects of interest (from Roni, 2005). Most appropriate study designs are listed in parentheses. BA = before-after study design, BACI = before-after control-impact, and EPT = extensive post-treatment design. Extensive design refers to a design that is spatially replicated (many study sites, reaches, or watersheds).

Number of projects	Spatial scale	
	Reach/local	Watershed/population
Single project	Does single project effect habitat conditions or biota abundance? (BA or BACI)	Does an individual project affect watershed conditions or biota populations? (BA or BACI)
Multiple projects	Do projects of this type affect local habitat conditions or biota abundance? (EPT or replicated BA or BACI)	A. What are the effects of a suite of different projects on watershed conditions or biota populations? (BA or BACI) B. What is the effect of projects of type X on watershed conditions or biota populations? (BA or BACI)

5.1.2.2 Define scale

Monitoring should be matched to the most appropriate scale for the target species or communities. Determining the scale of influence for physical habitat responses requires distinguishing between habitat, reach or sector, and network scale effects. However, for fishes and other mobile organisms, determining the appropriate scale requires differentiating between changes in local abundance and changes in population parameters at a watershed, network or even larger scale. Most research on habitat and biota, both for rehabilitation and other ecological studies, has focused on individual habitat units or a reach or sector scale. This information is important, but uncertainty about movement, survival, and population dynamics of biota prevent these reach-scale studies from addressing watershed or population-level questions. Studies designed to assess watershed or population-level effects provide the most valuable information but are often more difficult and costly to implement.

5.1.2.3 Monitoring design

Other important decisions including appropriate monitoring design, duration and scale of monitoring, sampling protocols, etc will flow from the key questions and specific hypotheses. The most difficult part and the greatest shortcoming of many rehabilitation evaluation programmes is the study design. Lack of reference sites[4], pre-project data, adequate treatments and controls, and various management factors limit the ability to determine the effects of rehabilitation actions. There are many potential study designs for monitoring single or multiple rehabilitation actions. None is ideal for all situations and each has its own strengths and weaknesses. These possibilities can be distilled down to a handful of experimental designs based on whether data are collected before and after treatment (before-after, or post-treatment designs) and whether they are spatially replicated or involved single or multiple sites (intensive or extensive). These basic designs can easily be modified for use in evaluating a variety of rehabilitation actions at various scales. No one design is correct for all situations – the key questions and hypotheses will help determine the most appropriate design.

5.1.2.4 Selecting monitoring parameters

The metrics and parameters selected for monitoring and measuring depend on the goals and objectives, key questions and hypotheses, definition of scale, and selection of study design. Selecting parameters also goes hand in hand with spatial and temporal replication and sampling schemes. Parameters and metrics should not be selected arbitrarily or simply because they were used in other studies. Monitoring parameters should be relevant to the questions asked, strongly associated with the rehabilitation action, ecologically and socially significant, and efficient to measure. For example, monitoring of riparian rehabilitation will likely be focused on indicators of plant growth and diversity as well as some channel features, while instream habitats improvement may focus on instream habitat features and changes in fish numbers or diversity. Moreover, to be useful, the parameter must change in a measurable way in response to treatment, be directly related to resources of concern, and have limited variability and not likely to be confounded by temporal or spatial factors.

The appropriate parameters to monitor will differ according to the type of rehabilitation as well as to any specific hypothesis. The choice of a parameter should in part be based on the different sources of spatial and temporal variability associated with that parameter. Both observation error and natural variability of a quantity will reduce the precision with which the mean of the quantity is estimated. Moreover, temporal variation within sites

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[4] Controls and references are inherently different. A control is a study location nearly identical to the treated location, with the exception that no treatment occurs. A reference is a site in a relatively natural state, representative of conditions before human disturbance or target conditions for a rehabilitation project.

and across sites can affect the usefulness of an indicator or parameter for detecting local and regional trends in biota or habitat. It is important to consider these different types of error when selecting monitoring parameters. Numerous publications discuss different parameters to measure and their strengths and weaknesses (Gibbs *et al.*, 1998; Osenberg *et al.*; 1994; Bain and Stevenson, 1999).

5.1.2.5 Number of sites and years to monitor

Determining the spatial and temporal replication needed to detect changes following rehabilitation can and should be established prior to monitoring. This will also help determine whether the initial parameters selected will be useful in detecting change to the rehabilitation action in questions. This can be done using relatively straightforward power analysis found in statistical software packages and statistical texts. Similarly sampling schemes for collecting data within a given study area are covered in similar texts (e.g. simple random, systematic, stratified random, multistage, double sampling, Line transect).

5.1.2.6 Implementing monitoring and reporting results

Once the monitoring programme has been designed and implemented, the results obviously need to be written up and published. While this seems intuitive, many studies on habitat rehabilitation have only been published as grey literature. Moreover, the published literature is likely biased towards projects that showed an improvement following rehabilitation. Rehabilitation actions are experiments and reporting both positive and negative findings are critical for improving our understanding of the effectiveness of different measures, spending limited rehabilitation funds wisely, and restoring aquatic habitats and ecosystems.

Guidelines – monitoring

i) ***Monitoring and evaluation of rehabilitation projects is critical to understanding the effectiveness of the actual rehabilitation activity and contributes to the technical and the cost effectiveness of any future projects of a similar nature.***

ii) ***Key factors to consider when developing a monitoring and evaluation programme for rehabilitation include:***

iii) ***Design of monitoring is best done as part of project design, not as an afterthought.***

iv) ***Hypotheses should be defined and an appropriate study design, and selecting sensitive parameters linked to the hypotheses.***

v) ***Monitoring should be sensitive to the scale and scope of the Rehabilitation activity.***

vi) ***Failure to detect significant changes in ecosystem processes, physical habitat, or biota is often due to poorly designed monitoring and not following the steps defined above.***

vii) ***Results should be reported and published for both successful and unsuccessful projects.***

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7. GLOSSARY

Acquisition	The purchasing of a piece of land for the protection or restoration of plants and animals. Compare *easement*.
Anadromous	An organism that migrates from the sea to freshwater for reproduction.
Assemblage (fish)	All species living in a habitat or ecosystem that do not necessarily interact ecologically.
Bankfull	The level at which water overflows the channel to inundate the floodplain.
Bankfull width	Channel width between the tops of banks on either side of a stream; tops of banks are the points at which water overflows its channel at bankfull discharge.
Barrage	A dam or other obstruction that impounds water.
Baseline monitoring	Characterizing existing biota, chemical or physical conditions for planning or future comparisons. Compare *status*, *trend*, *implementation*, *effectiveness, and validation monitoring*.
Basin	*See watershed.*
Benthic	Of, related to, or living in the bottom substrate/ water interface of a lake or stream.
Biotic integrity	The capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the regions.
Biomass	Total amount of all living organisms in a biological community, as in a unit area or weight or volume of habitat.
Biota	Flora and fauna of a region.
Brush bundles	Groups of trees and branches placed into a lake or stream to create habitat and cover for fish. Often used in conjunction with other habitat rehabilitation techniques.

Groin	A jetty extending from the bank into the channel designed to protect or stabilize a bank or trap gravel and sediment sands.
Gullying	Erosion of soil by formation or extension of channels (gullies) from surface runoff.
Habitat	In this publication, the term refers to the aquatic environment that fish experience and not those landscape processes or attributes outside streams that alter habitat conditions.
Habitat unit	Distinct geomorphically defined area within a stream reach, such as a pool, a riffle, a glide, etc. Sometimes called a *mesohabitat*.
Hypereutrophic	Nutrient levels such that the conditions include dense algal blooms, low oxygen levels inhabited only by species tolerant of low dissolved oxygen conditions.
Hypolimion	The lowest level in a stratified lake situated below the thermocline.
Ichthyocenosis	European term for the community of fish species, that interacts ecologically, associated with a particular habitat or ecosystem.
Implementation monitoring	Evaluating whether the restoration project was constructed (implemented) as planned. Compare *baseline, status, trend, effectiveness, and validation monitoring*.
Instream vegetation	Vegetation that grows in the channels of rivers and in shallow areas of lakes and reservoirs. It mostly consists of submersed, emergent and floating plants.
Large woody debris (LWD)	Large piece of woody material such as a log or stump that intrudes into or lies entirely within a stream channel; LWD typically is defined as wood greater than 10 cm in diameter and 1 m in length, but other minimum size criteria also are used. See also *woody debris*.
Levee	An embankment or dike constructed of earth, rock or other material to prevent a river from overflowing.

Brush park Submerged or partially submerged structures made of brush, branches, and aquatic vegetation secured in place with poles or fences. They are designed to provide fish rearing areas, fishing opportunity, or a refuge for fish. They vary in size from a few square meters to several hectares and are placed in lakes, streams, and brackish waters.

Canalization Straightening, narrowing, and deepening of a stream channel to improve navigation, move water faster, prevent flooding of human infrastructure, provide for construction of infrastructure, or other human uses. Often includes removal of debris and channel obstructions that may impede flow conveyance. See also *channalization.*

Catchment *See watershed.*

Channelization Straightening, narrowing, and deepening of a stream channel to improve navigation, move water faster, prevent flooding of human infrastructure, provide for construction of infrastructure, or other human uses. Often includes removal of debris and channel obstructions that may impede flow conveyance. See also *canalization.*

Channel unit See *habitat unit*.

Coarse particulate organic matter (CPOM) – Consists of leaves, flowers and other small debris

Coarse sediment Generally, greater than 2-mm diameter, which is gravel, cobbles, or boulders. Compare *fine sediment*.

Control site A study location nearly identical to the treated location, with the exception that no treatment occurs. See also *reference site*.

Community (fish) A group of species that living in a habitat or ecosystem the interact ecologically.

Copse A small woodland

Creation (habitat) Construction of a new habitat or ecosystem where it did not previously exist. This is often part of mitigation activities.

Culvert A transverse pipe or totally enclosed drain under a road or railway. Typically used to convey stream flow under a road or other manmade construction.

Deflector One of many types of wood or stone structures placed perpendicular or at angle to a stream bank to deflect flow and create a pool and improve fish habitat or prevent a bank from eroding.

Dystrophic A specialized class of highly acidic lakes associated with peat bogs and some types of rainforest areas.

Easement In restoration ecology, it refers to acquiring a portion of the rights to a land to allow for, or protect from, a specific use. Technically defined as the nonpossessory interest granted in the lands of another, established to obtain certain limited rights (e.g. development rights, but never the right to “quiet enjoyment”) that are often in perpetuity but sometimes for only set periods of time. Compare *acquisition*.

Ecosystem Dynamic and holistic system of all the living and dead organisms in an area and the physical and climatic features that are interrelated in the transfer of energy and material.

Effectiveness monitoring Evaluating whether actions had the desired effects on physical processes, habitat, or biota. Compare *baseline, status, trend, implementation, and validation monitoring*.

Emergent vegetation This includes plants that are normally rooted in the bottom but whose vegetative growth is mostly in the air such as *Juncus* and *Phragmites*.

Enhancement (1) Habitat – To improve the quality of a habitat through direct manipulation. It does not necessarily seek to restore processes or conditions to some predisturbed state. Some practitioners call this partial restoration. Compare rehabilitation and restoration.
(2) Fish culture – Stocking or planting of cultured fish into waters to increase production or harvest of fish.

Eutrophic	Nutrient-rich, highly productive; inhabited by species that are tolerant of periodic lowering of oxygen levels.
Exclosure	Fencing an area to prevent (exclude) access of livestock or other ungulates.
Fine sediment	Generally, less than 2-mm diameter, typically composed of clay, silt, or sand. Compare *coarse sediment*.
Floodplain	A flat depositional feature of a river valley adjoining the channel, formed under present climate and hydrological conditions, and subject to periodic flooding.
Floodplain vegetation	Plants living on floodplains ranging from grasses that form floating mats during the wet season to large trees that form floodplain forests. Floodplain grasslands are widely converted to agriculture, particularly for rice. Floodplain vegetation can range from highly seasonal areas to permanent wetlands. It is typical of seasonally flooded river wetlands (floodplains) and marginal areas of lakes.
Floating vegetation	Plants that may be either rooted in the bottom with floating leaves, such as *Nymphaea* or *Lotus* or free floating on the surface, such as *Eichhornia*; *Pistia* or *Salvinia*.
Fry	Brief transitional stage of recently hatched fish that spans from absorption of the yolk sac through several weeks of independent feeding.
Gabion	Wire rectangular or round basket placed in a stream channel and filled with gravel, gobbles, boulders or other hard material to serve as bank protection or to create a weir to trap gravel, create a pool, and improve fish habitat.
GIS (geographic information system)	A computer system for assembling, storing, manipulating, and displaying geographically referenced information.

Macroinvertebrate	Animal without a backbone, living one stage of its life cycle, usually the nymph or larval stage. Macroinvertebrates are visible without magnification, and many are benthic organisms (see *benthic*).
Main stem	Principle stream or channel of a stream network.
Mesotrophic	Intermediate nutrient availability and biological productivity; inhabited by a wide range of species.
Migration	The intentional movement of large numbers of fish from one type of habitat to another, usually necessary for completion of the life cycle.
Mitigation	Action taken to alleviate or compensate for potentially adverse effects on an aquatic habitat that has been modified or lost by human activity.
Monitoring	Systematically checking or scrutinizing something for the purpose of collecting specific categories of data, especially on a recurring basis. In ecology, it generally refers to systematically sampling something in an effort to detect or evaluate a change or lack of change in a physical, a chemical, or a biological parameter. Compare *baseline, status, trend, implementation, effectiveness, and validation monitoring*.
Movement (fish)	Differs for migration in that they are individual often and not associated with specific life functions.
Nutrient enrichment	Addition of organic or inorganic compounds to a water body to increase background levels of nutrients (e.g. phosphorous, nitrogen).
Oligotrophic	Nutrient-poor, biologically unproductive; inhabited by species requiring high levels of oxygen and clean waters.
Parameter	Quantitative physical, chemical, or biological property, such as water temperature or biota abundance, whose values describe the characteristics or behavior of an individual, a population, a community, or an ecosystem. See also *metric* and *variable*.

Rehabilitation	(1) To restore or improve some aspects of an ecosystem but not fully restore all components for a number of reasons depending on the requirements of society, the use to be made of the resource and the social requirements of the system. (2) A general restoration term that can include habitat restoration, improvement, enhancement, reclamation or mitigation. Some practitioners call this partial restoration. Compare enhancement and restoration.
Remote sensing	Gathering data from a remote station or platform, as in satellite or aerial photography.
Restoration	(1) Returning the ecosystem to some predisturbed condition. Some practitioners call this full restoration. (2) A general term for referring to various enhancement, improvement, and rehabilitation actions. *Compare enhancement and rehabilitation.*
Riffle	Shallow section of a river or stream, with moderate to rapid flow and with surface turbulence.
Riparian	The banks of a river or the terrestrial aquatic interface. That part of the terrestrial landscape that exerts a direct influence on stream channels or lake margins, and the water or aquatic ecosystems.
Riparian vegetation	The complex of plants living along the banks or rivers or the shoreline of lakes. Riparian plants range from floating mats of grasses through emergent vegetation to water loving bushes and trees. There is usually a clear succession of plant types related to the extent of contact with water.
River network	The complex of river tributaries and channels draining a basin.
Rubble matt	The placement of rocks, boulders, or concrete into the stream channel to create diverse flow and velocities and create riffles or fast water habitats for fishes and other aquatic organisms.
Salmonid	Fish of the family Salmonidae, including salmon, trout, and chars.

Periphyton	Sessile organisms, such as algae, that live attached to surfaces or rocks and other material projecting from the bottom of a freshwater aquatic environment.
Phytoplankton	A complex mix of algae that floats in the water column, usually at or near the surface.
Polder	Areas of wetland or seasonably flooded riparian land that are completely enclosed by raised banks to exclude the water. These are usually built in the interest of agriculture of habitation. The banks are often pierced by a sluice that controls entry of water into the enclosed area.
Primary production	Creation of organic matter (biomass) by photosynthesis or chemosynthesis.
Primary productivity	Rate at which organic matter (biomass) produced by photosynthesis or chemosynthesis is stored in an ecological community or group of communities. Compare *secondary productivity*.
Reach	A geomorphologically similar stream section or a section of stream as defined by two selected points.
Redd	Nest in gravel, dug by a fish for egg deposition, and associated gravel mounds.
Reference site	Site in a relatively natural state, representative of conditions before human disturbance. See also *control*.
Reclamation	Converting land from one type of use to another which may not necessarily have been its original undisturbed state. Also can be used when returning an area to its previous habitat type but not necessarily fully restoring all functions.

Secondary productivity	Rate at which primary (plant and organism) material is synthesized into animal tissue per unit area in a given time period. Compare *primary productivity*.
Sector	A portion of a lake, usually ecologically homogeneous, equivalent to a reach in a river.
Semi-migratory (fish)	Fish species that undertake short distance, local migrations – often not totally necessary for completion of life cycle and undertaken by only a proportion of the population.
Side channel	A subsidiary or overflow channel branching from the primary stream channel, typically conveying a small fraction of the total stream flow.
Sill	A low weir partially buried in the stream bottom designed to aggrade or maintain the channel level.
Silviculture	In forestry or forest management, the care, cultivation, and harvest of trees. In restoration ecology, the term generally refers to planting, removing, or growing trees and other vegetation to restore certain forest characteristics.
Status monitoring	Characterizing the condition (spatial variability) of physical or biological attributes across a given area. Compare *baseline, trend, implementation, effectiveness, and validation monitoring*.
Submersed vegetation	Includes plants that grows underwater for their whole life cycle and are usually rooted in the bottom of lakes and rivers. Typical examples are *Hydrilla* and *Potomogeton*.
Submerged vegetation	Includes plants that grow in areas where they are seasonally inundated. These include floodplains and lake shores. These plants generally have a dry-season phase when they are part of the terrestrial flora and a wet-season phase when they are flooded. Typical examples are grasses such as *Oryza, Vossia* or *Echinochloa*.

Swamp vegetation	Typically consists of a complex of sedges (*Papyrus*, *Carex*) and small scrub bushes and is characteristic of permanent shallow wetlands. Open waters of the swamp may be colonized by submersed, floating and emergent vegetation.
Thinning	Removal of trees or other vegetation to allow for increased growth of other trees or vegetation.
Trend monitoring	Monitoring changes in biota or physical conditions over time. Compare *baseline, status, implementation, effectiveness, and validation monitoring*.
Validation monitoring	Evaluating whether the hypothesized cause-and-effect relationship between restoration action or other treatment, and physical and biological response were correct. Sometimes considered a part of effectiveness monitoring. Compare *baseline, status, trend, implementation, and effectiveness monitoring*.
Watershed	(1) The ridge or crest line dividing two drainage areas (British usage) (2) Entire land-drainage area of a river. Also called basin, drainage basin, or catchment (North American usage).
Woody debris	Trees and branches falling into the river channel and floodplain, including *large woody debris* as well as fine and *coarse particulate organic matter* (CPOM)