Environmental Aspects of Integrated Flood Management

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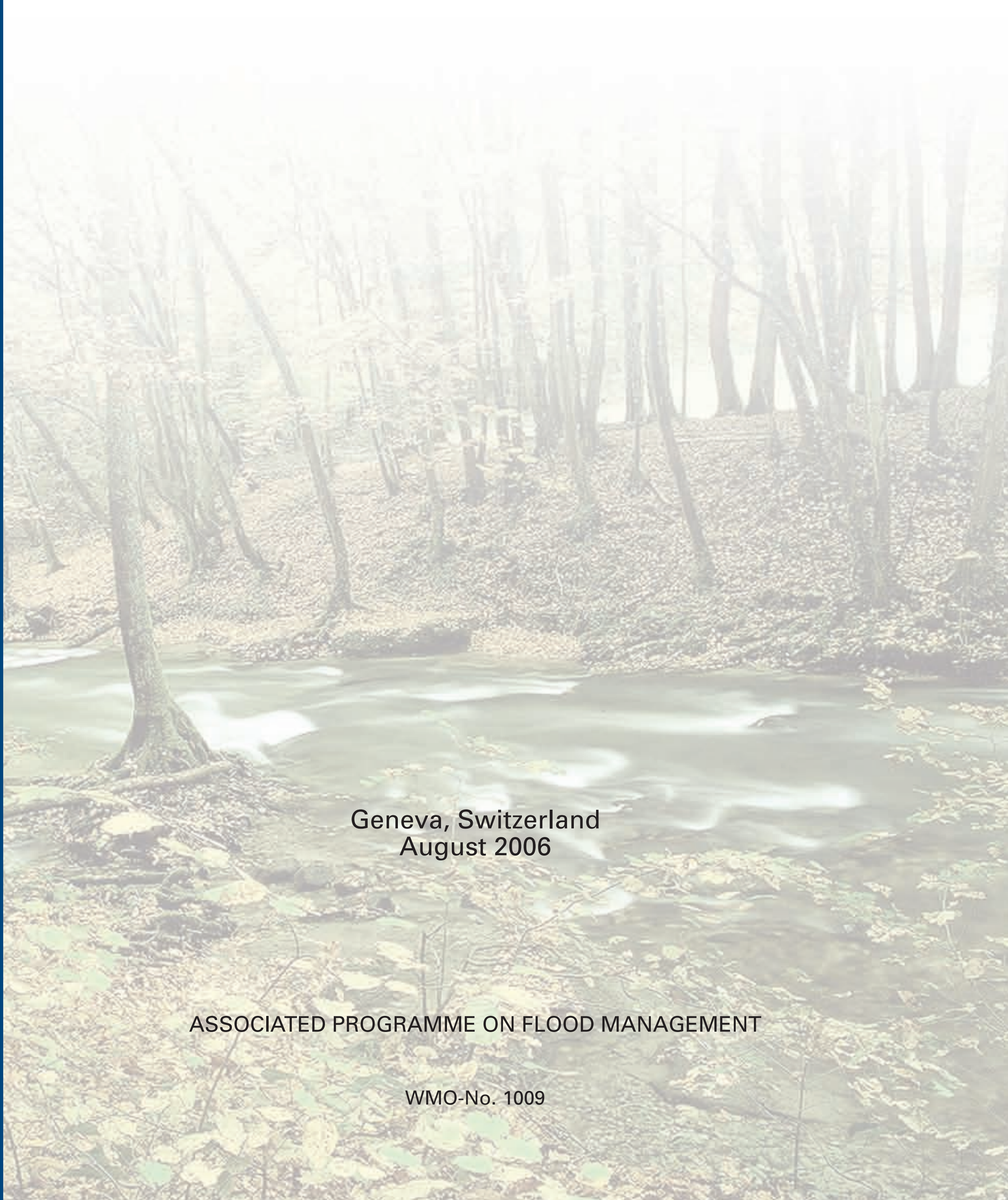

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The Associated Programme on Flood Management (APFM) is a joint initiative of the World Meteorological Organization and the Global Water Partnership. It promotes the concept of Integrated Flood Management (IFM) as a new approach to flood management. The programme is financially supported by the Governments of Japan and the Netherlands.

The World Meteorological Organization (WMO) is a specialized agency of the United Nations. It coordinates the activities of the meteorological and hydrological services of 187 countries and territories and as such is the centre of knowledge about weather, climate and water.

The Global Water Partnership (GWP) is an international network open to all organizations involved in water resources management. It was created in 1996 to foster Integrated Water Resources Management (IWRM).

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CONTENTS

EXECUTIVE SUMMARY

Integrated Flood Management (IFM) addresses issues of human security and sustainable development from a perspective of flood management, within the framework of Integrated Water Resources Management (IWRM). Some of the underlying causes that make it difficult to integrate the growing concerns regarding environmental degradation into sound flood management practices revolve around communication gaps between the various discipline groups involved – understanding the varying perspectives of sustainable development. This publication presents IFM approaches with special reference to environmental aspects and is an attempt to narrow this gap. It has been prepared primarily for flood managers to enable them to understand the range of environmental issues involved in flood management. At the same time, it provides useful information for policy makers, environmental groups, NGOs and communities, to help them assess flood risks in relation to environmental concerns and sustainable development.

There are no universal criteria to determine environmentally friendly flood management practices. It is crucial to adopt practices that suit the particular circumstances in a given hydro-climatic, topographical and socio-economic setting and follow a rational and balanced approach in addressing environmental issues in flood management.

Setting the scene

Historically, flood plains have been the preferred places for socio-economic activity as is evident from the very high densities of human settlement found there. Flood management plays an important role in protecting people and their socio-economic activities in flood plains from flooding. However, strategies that largely rely on structural solutions (e.g. dams and reservoirs, embankments, bypass channels, etc.), unfortunately alter the natural environment of the river, resulting in loss of habitats, biological diversity and ecosystem productivity. The need for sustainable development has highlighted the importance of addressing the negative consequences of such flood control and protection measures on the environment and has led to a paradigm shift from flood control to flood management.

Environmental degradation has the potential to threaten human security, including life and livelihoods, and food and health security. Ecosystems, such as forests, wetlands and lakes provide enormous services to us. These services include food provision, drinking water supply, water purification, regulation of flow regimes, and sustaining cultural heritage. Natural ecosystems are highly resilient, at the same time it is difficult to restore them when they are destroyed. Therefore, the key issue in sustainable development in general, and water resources management in particular, is to secure the capacity of ecosystems to absorb continuous disturbances, so that they continue to provide the required services. Factoring environmental impacts in flood management activities is, therefore, important within the context of both sustainable development and human security.

Extreme demands on natural resources due to population growth have forced people and their property to move closer to rivers in many parts of the world. Further, flood control and protection measures have encouraged people to utilize newly protected areas extensively, thereby increasing flood risks and consequent losses. At the same time, various other activities for development and improvement of life, livelihoods and human security are drivers of environmental and ecosystem degradation. Flood management policies and practices have to be viewed within the overall context of such drivers. It is, therefore, extremely important to balance development imperatives, flood risks, social and economic vulnerability, and sustainable development vis-à-vis the preservation of ecosystems.

Assessing flood management options through scientific knowledge

Under natural conditions, rivers continuously migrate across their floodplain belt and change the configuration of the landform. Flow and sediment regimes, interacting with bed and bank materials and with riverine vegetation, create and destroy fluvial features, thereby providing a variety of habitats for diverse biotic communities. River morphology and the diversity and density of habitats are in a state of dynamic equilibrium. Seasonal floodplain inundation is essential to maintaining a complex river corridor (i.e., the river channel and its associated flood plain). Flooding not only allows aquatic organisms to move out of or into the main channel, but also causes morphological change, creates new habitats, deposits silt and fertile organic material, sustains wetlands, renews floodplain ponds, and temporarily stores water on the flood plains, alleviating flooding downstream. Ecological and morphological connectivity across longitudinal (upstream catchment and downstream corridor reaches), lateral (between the river and its flood plain), and vertical (surface with subsurface zones) dimensions need to be maintained with adequate quality and seasonal variability of water flows.

Fluvial processes also greatly influence estuarine and deltaic processes since rivers provide the main sources of fresh water, sediments and nutrients for them. Morphological changes in river deltas result from the interaction of fluvial and marine forces in the vicinity of the river mouth. Dams and diversion works have the potential to alter the flow regime and consequently the sediment supply to coastal areas, thereby influencing morphological and ecological processes therein. Protection of coastal ecosystems thus lies in synergizing IWRM, and IFM as its subset, with Integrated Coastal Zone Management (ICZM).

Structural flood control and protection works, e.g. dams and reservoirs, embankments, channelization, etc., have the potential to alter flow regimes, fix river shape or separate river channels from their flood plains. As such, they tend to impede natural ecological and morphological processes and oversimplify the river corridor, resulting in a spatially homogeneous ecosystem, which is not able to provide varied habitat features for a diverse range of species. It is, therefore, important to maintain the structure and function of fluvial ecosystems because most of the ecosystem services provided by river corridors depend on these, and they are lost when rivers are simplified.

The need to maintain environmental flows with their associated flow and sediment regime variability has to be appropriately addressed at the design and operation stages of flood control and protection works in an attempt to attain a dynamic equilibrium under new flow and sediment regimes. This helps in maintaining ecological health. Non-structural measures such as land use regulations, flood forecasting and warnings, use of natural ecosystems, etc., play an important role in limiting negative environmental impacts and should be actively considered as vital options, both as independent and complementary measures.

Factoring environmental considerations in decision-making processes

There are various constraints – physical, technical, economic and political – in any flood management decision-making. Societal values, perceptions of risks and the trade-offs between development and environmental preservation differ among various stakeholders, but need to be taken into account. In order to minimize subjectivity in decision-making, an environmentally sensitive framework needs to be established following a threefold approach of avoiding, reducing and mitigating the adverse environmental impacts without compromising on flood management objectives. Such a framework will help to minimize the negative impacts of flood management interventions that limit natural productivity, ecosystem health and their services.

Scientific understanding and analysis

Scientific knowledge of basic concepts concerning the morphology and ecology of rivers and their flood plains is fundamental to understanding the ecosystem processes in a river basin and the impacts of flood management measures on the ecosystems. Environmentally sensitive design, execution and operation of new projects; and mitigation of adverse impacts of existing works through better operation and restoration can be undertaken, only if such scientific concepts are understood. Integrated Flood Management calls for a multidisciplinary approach to flood management, which promotes a dialogue among professionals from various disciplines, coming from different paradigms, to explore shared perceptions and common goals.

Environmental assessment

Environmental assessment is a tool to identify the more intensive examination required for decisions that may have significant adverse environmental impacts. Environmental assessment is applied at various levels of decision-making, ranging from policy and planning to project design and implementation. For effective environmental assessment, it is important to start at the strategic level and facilitate a dialogue between environmental and development authorities as well as informed public representatives. Information exchange and utilization, with readily understandable data, facilitate communication among various stakeholders and experts, play a vital role in ensuring close collaboration between the various stakeholders and help in keeping the decision-making process transparent.

Environmentally sensitive economic analyses

Environmentally sensitive economic analysis plays a key role in trade-offs and conflict situations. Multi-criteria analysis (MCA) is useful in ranking options, short-listing a limited number of options for subsequent detailed appraisal, e.g. cost-benefit analysis (CBA). Multi-criteria analysis can be used for stakeholders to explore the nature of the choices, determine the critical factors, discover their own preferences and simplify the process of selecting critical options. Since economic evaluation involves societal values, it is appropriate to carry out environmentally sensitive economic analysis in close consultation and participation with the public affected by the projects.

Stakeholder involvement

Genuine stakeholder involvement is at the core of decision-making processes at various levels in flood management. The main purpose of stakeholder involvement is to ensure implementation of IFM principles where stakeholders participate in identifying, shaping, developing, logically validating and implementing the plans and projects, as well as in assessing, monitoring and evaluating their impacts. Consultation and public involvement is also the key to carrying out environmental assessment and environmentally sensitive economic analysis. Interaction with people and eliciting feedback allows affected communities to influence the decision-making processes by raising issues that should be considered at the various stages.

Adaptive management approach

While understanding of river morphology and ecology is the key to achieving IFM, scientific knowledge about the existing conditions of ecosystems is, however, fragmentary and the impacts of human interventions on ecosystems are not fully understood. In order to account for this lack of scientific certainty, precautionary principles are recommended. Adaptive management approaches such scientific uncertainties through continuous monitoring and evaluation of applied strategies, incorporating new knowledge as it becomes available, and modifying approaches if required.

Monitoring

The importance of monitoring has been recognized from various perspectives: starting with pre-plan monitoring of various natural processes to provide the basic input for assessment of resources, risks and development options. At the development planning level, it is focused on assessing the impacts of actions taken, as indicated in the environmental assessment at the strategic level. During and post-implementation, monitoring is important at the project level, in order to assess whether the flood management measure has in fact succeeded in meeting its desired objectives. Lessons learned through monitoring and evaluation can improve the methodology applied in future plans and project designs.

Enabling mechanism

Most countries lack the organizations capable of adopting integrated approaches and the investment to support effective organizational learning and cross-organizational interactions. The communication gap among various professional streams and between experts and the public at large further complicates the process of putting such a framework into practice. Laws can protect and entrench the rights and interests of the environment that might otherwise have no influence in the decision-making. Behavioural change between the different institutions and organizations is needed, along with capacity-building at various levels in order to develop institutions that can build such a framework, supported by legal mechanisms.

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1. INTRODUCTION

Historically, flood plains have been the preferred place for socio-economic development due to their development potential, as is evident from the very high densities of human settlement along rivers throughout the world,[1*] e.g. Bangladesh[2] and Japan.[3] Modern society places extreme demands on all such natural resources. In developed economies, where commercial and residential use of flood plains has contributed to their economic success, improvements in flood management have encouraged people and their assets to move closer to rivers, thereby increasing flood risks and consequent losses. There is clear evidence that at the global level, economic losses caused by flooding are increasing.[4,5] This, in part, is a reflection of rapidly growing populations, expanding economic growth and development (e.g. urbanization), increased investment in infrastructure, in combination with uncertainties such as climate variability and change. Reducing risks by restricting the occupation of flood plains, however, limits the potential of these areas for socio-economic development.[6]

1.1 From flood control to Integrated Flood Management

Flood and floodplain management play important roles in protecting people and socio-economic development. Until recently, flood control and protection have been engineering-centred, with little or no consideration being given to the social, cultural and environmental effects of the selected strategy, nor to long-term economic concerns. They have largely relied on structural solutions (e.g. embankments, bypass channels, dams and reservoirs, etc.), which have unfortunately changed flow regimes, fixed river shape or have separated river channels from their flood plains, resulting in loss of habitats, biological diversity and productivity. During the past half century, flood control and protection have slowly moved from an emphasis on structures towards incorporating complementary non-structural measures such as flood forecasting and land use regulations.

The adverse impacts of some of these structural measures and the growing concern for sustainable development have highlighted the need to address the negative consequences of flood control and protection measures on the environment. Over the past couple of decades, increasing environmental concern for sustainable development has facilitated a shift from "flood control" towards "flood management". It is now recognized that floods are a natural phenomenon, which determine the natural regime of a river; and that any structural interventions have impacts on the natural environment, which can cause environmental degradation and impair services provided by ecosystems.

The need for the paradigm shift from flood control to flood management is enshrined in the concept of Integrated Flood Management (IFM): a process promoting an integrated approach to flood management. Integrated Flood Management aims at maximizing the net benefits from flood plains and minimizing loss of life from flooding. The essential elements of IFM are:

- Adopting a basin approach to flood management;
- Bringing a multidisciplinary approach in flood management;

* Superscripts indicate the number of the endnotes given at page 65 onwards.

- Reducing vulnerability and risks due to flooding;
- Enabling community involvement; and
- Preserving ecosystems.

Integrated Flood Management addresses issues concerning human security and sustainable development from the perspective of flood management, within the framework of Integrated Water Resources Management (IWRM). As such, it synergizes with Integrated Coastal Zone Management (ICZM), since the lower reaches of a river estuary and coastal zone form an integral part of the river basin. However, despite the wide acceptance of an integrated approach to water resources management as a concept, there are still certain constraints in adopting an integrated approach to flood management. In practice, flood management largely remains a mono-disciplinary and mono-functionary pursuit.

1.2 Purpose and scope of the publication

Different disciplinary groups, such as environmental scientists, ecologists, flood managers and hydrologists, approach sustainable development from different perspectives. Some of the underlying causes that make it difficult to integrate the growing concern regarding environmental degradation into sound flood management practices revolve around communication gaps; and understanding varying perspectives to sustainable development. There are differences in the terminology used by various disciplines and a lack of appreciation for the issues raised by the different groups. Effective communication and understanding between the various stakeholders and experts are therefore vital. This publication is an attempt to narrow the gap.

This publication is primarily directed to flood managers, to enable them to understand the range of environmental issues involved in flood management. At the same time, it provides useful information for policy makers, environmental groups, NGOs and communities, to help them to understand flood risks in relation to environmental concerns and sustainable development. It is aimed at improving communication and understanding between different disciplines, stakeholders and experts. Therefore, it avoids highly technical details. The facts are based on existing scientific knowledge and referenced.

It is recognized that there are no universal solutions for environmentally friendly flood management practices. It is crucial to adopt practices that suit particular circumstances in a given hydro-climatic, topographical and socio-economic setting in a basin. Therefore, this publication does not attempt to be a guideline or manual prescribing procedures or steps. Rather, it provides a rational and balanced way of addressing environmental issues in flood management. The publication focuses on environmental issues directly related to flood management, even though it is recognized that pollution also degrades water quality and the health of riverine ecosystems. The water pollution aspects form part of IWRM, of which IFM is a subset.

The publication looks at how environmental considerations can be appropriately incorporated in flood management practices and discusses issues related to:

- Balancing development imperatives and flood risks in relation to sustainable development;
- Understanding hydrological, morphological and ecological concepts relevant to floodplain processes;
- Recognizing environmental impacts of flood management measures;
- Resolving conflicting objectives and situations through trade-offs among various stakeholders;
- Adopting environmentally friendly flood management approaches; and
- Living and working with nature.

Chapter 2 describes the importance of sustainable development and of maintaining a balance between economic development, environmental protection and human security. As such, it depicts how development imperatives and environmental degradation are fundamentally linked. Eco-hydrology/eco-hydraulics, the science that studies the interactions between hydrology/hydraulics and ecosystems; and river morphology, which explores fluvial landforms, provide important inputs to IFM. Therefore, Chapter 3 describes basic concepts of river morphology and ecology, and how these are driven by flow regimes: this is the key to understanding the impacts of flood management measures and to implementing environmentally friendly designs for new projects. Chapter 4 discusses the role of the ecosystem in regulating the hydrological cycle and its potential and limits as a complementary option in flood management. Chapter 5 describes some of the environmental consequences of structural flood management measures, especially in terms of flow regime, sediment transport, water quality and biodiversity. It also explores possible options to avoid, reduce or mitigate the negative consequences.

Chapter 6 places environmental concerns at the heart of decision-making processes. It describes how environmental considerations can be appropriately incorporated into decision-making at the policy level, basin planning level and project design level through a framework consisting of relevant elements of an environmentally friendly approach within IFM. Given the uncertainties in the scientific understanding of environmental issues, it looks at adaptive management approaches supported by monitoring and evaluation and, finally, identifies the enabling requirements.

2. SETTING THE SCENE: ENVIRONMENT AND SUSTAINABLE DEVELOPMENT

Ecosystems provide enormous benefits to humans. Human security and well-being are closely related to maintaining ecosystems and avoiding environmental degradation. Human ingenuity is presented with a dilemma between development imperatives and environmental degradation. Issues of sustainable development, ecosystem services in the development process, human security and the related development imperatives are discussed, from a flood management perspective, in this chapter.

2.1 Sustainable development

Towards sustainable development

The concept of "sustainable development" has been at the centre of the environment and development debate since the Conference on Human Environment in Stockholm in 1972.[7] Sustainable development is: "the development that meets the needs of the present, without compromising the ability of future generations to meet their own needs".[8] At the same time, "the right to development is an inalienable human right and an integral part of fundamental human freedoms".[9] It is recognized that natural resources, the environment and development are interdependent.[10] Human development is closely related to and dependent on our natural surroundings and resources, including water, land, agriculture and forests. In developing countries, in particular, the livelihoods of millions of people depend directly on these natural resources, as there are often limited alternatives for economic growth and progress.

Much development in the past has taken place at the expense of natural resources, and has affected natural ecosystems and their ecological functions. It is increasingly recognized that present and future development needs have to be fulfilled in conjunction with environmental protection. The Plan of Implementation[11] agreed at the World Summit on Sustainable Development recognizes that human activities are having an increasing impact on the integrity of ecosystems that provide essential resources and services for human well-being and economic activities. Such an approach clearly is not sustainable in the long term. What is needed is a change in our perceptions of how we relate to our natural environment, and the influence that could have on the quality of life in the future. Thus, to reverse the current trend in natural resource degradation at the earliest opportunity, it is necessary to implement development strategies that protect ecosystems, through integrated management of land, water and living resources, while strengthening regional, national and local capacities. These principles have been widely accepted in the management of water resources through a paradigm shift in thinking towards IWRM.

Sustainable development, human security and the environment

Human security, which encompasses the physical security of individuals and communities, but also economic security, food security, health security, environmental security and political security, is embedded in the concept of sustainable development. Environmental security implies a healthy environment as opposed to environmental threats, when resources are mismanaged and/or degraded. The relationship between human security and the environment is most pronounced in areas where human dependence on access to natural resources is greatest. When these resources are threatened because of environmental changes, human security is also threatened. As a result, people are forced to move from rural areas to marginal lands or urban settlements, starting another cycle of unsustainable development and insecurity.

From the flood management perspective, environmental degradation has the potential to threaten human security in many different ways. First, it can increase the magnitude and frequency of flood hazards. Second, by affecting other components of human security such as economic and food security (e.g. land degradation affecting agricultural productivity) and health security (e.g. polluted water), it increases the vulnerability of those exposed to such hazards. Adequate consideration of environmental impacts in flood management activities is therefore important within the context of both sustainable development and human security.

2.2 The environment and ecosystems

The environment can be defined as "the surroundings in which an entity operates. This includes air, water, land, natural resources, flora, fauna, humans and their interrelation".[12] The climate, the physical setting and the resulting river flow regimes, set within various ecosystems, with human activities superimposed, determine the environment of a flood plain. Human activities have profound impacts on the various ecosystems within the environment.

An ecosystem is a dynamic system of plant, animal and microorganism communities and their non-living environment, interacting as a functional unit.[13] Ecosystems, such as forests, wetlands and lakes comprise all the organisms present in the area along with their physical, or abiotic,[14] environment and their mutual interactions. An ecosystem has a structure or organization, given by the different interacting living and non-living components. The higher the number of system elements, comprising an ecosystem and their mutual interactions, the more effectively any disturbances within the ecosystem can be balanced out. Hence ecosystems are resilient (able to return to their original state after a perturbation), but at the same time difficult to recreate if destroyed.

Ecological processes keep the planet fit for life by providing food, air to breathe, medicines and much of what we call "quality of life". The immense biological, chemical and physical diversity of the earth forms the essential building blocks of ecosystems.[15] The key issue in sustainable development in general, and water resources development in particular, therefore, is to secure the capacity of the systems to absorb continuous change without losing their capacity to provide a continuous supply of ecological goods and services.[16] It is extremely important, therefore, to understand and to protect complex ecosystems such as forests, wetlands and river ecosystems; not only their structures but also their functioning.

On a management level, development strategies, which consider the need to protect ecosystem functioning, are termed "ecosystem approaches". Within such an approach, one particular resource, activity or set of environmental goods and services cannot be considered separately from others. Thus, "the ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way...".[17] Ecosystem approaches are applicable at all scales, from the local to the global. Flood plains present the best option for livelihoods, particularly in developing countries where poverty alleviation and socio-economic development are strongly dependent on the exploitation of natural resources. Sustainable development, therefore, has to address the needs of development while maintaining the natural environment of river corridors[18] to the greatest extent possible. Integrated Flood Management, which has environmental protection as one of its objectives, encompasses the 12 principles of the ecosystem approach.[19] Table 1 provides an overview of these principles and their relationship with IFM principles.

2.3 Ecosystem services

Ecosystem services for people

The Millennium Ecosystem Assessment describes ecosystem services as "the benefits that people obtain from ecosystems".[20] These include provisioning, regulating, and cultural services that directly affect people, and the supporting services needed to maintain other services. Many of these services are closely inter-linked (see Figure 1).

Provisioning services are the products obtained from ecosystems such as food, fibre, fuel, genetic resources, biochemicals, natural medicines, pharmaceuticals and ornamental resources. Supply

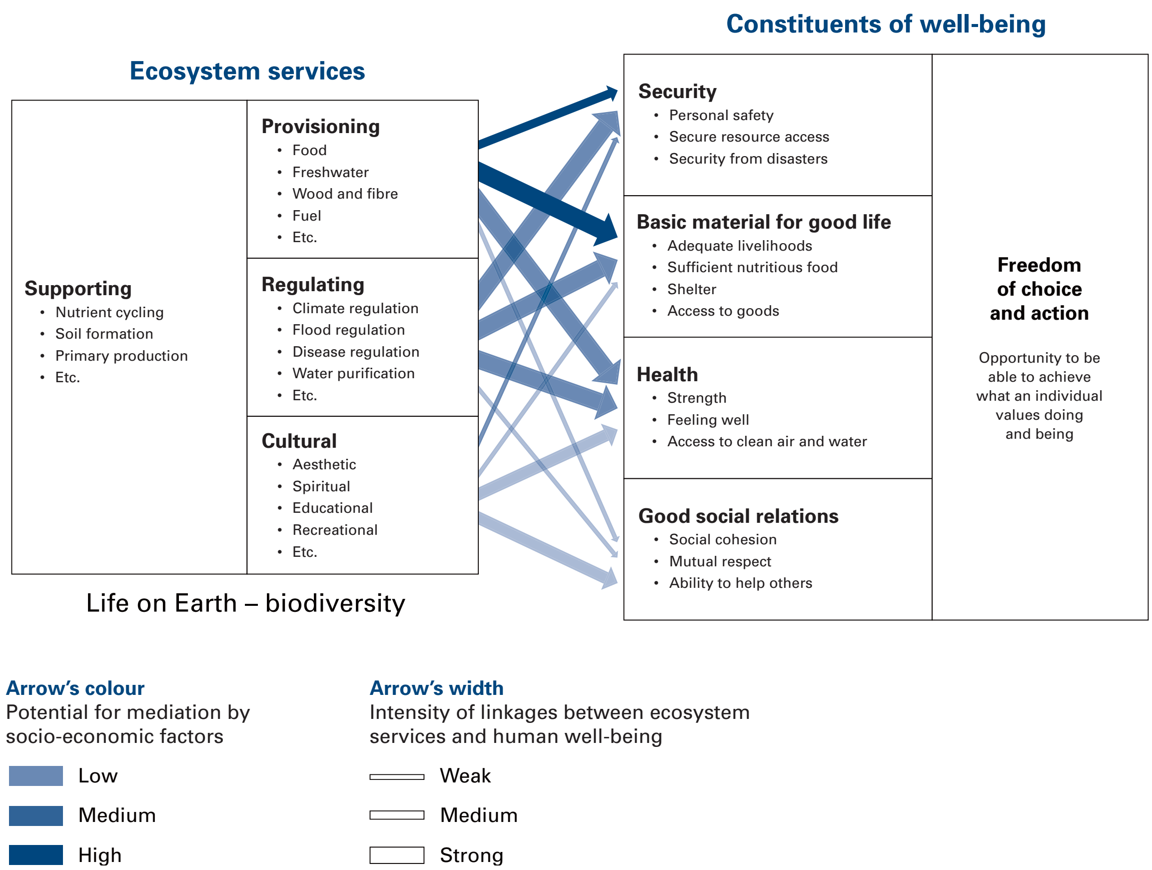

Figure 1. Linkages between ecosystem services and human well-being
(*Source:* Millennium Ecosystem Assessment, 2005)

of fresh water is one of the most vital provisioning services of ecosystems, as are the many different freshwater organisms used as food and fibre.

Regulating services – ecosystem processes regulate air quality, climate, disease, pests, pollination, erosion, etc. Ecosystems can help filter out and decompose organic waste introduced into inland waters and coastal and marine ecosystems providing water purification and waste treatment services. They can also assimilate and detoxify compounds through soil and subsoil processes. Water flow is regulated by ecosystems, both in timing and magnitude of runoff and aquifer recharge. If ecosystems are not maintained properly, their functions will be disturbed, thereby decreasing their services and changing their response to river regimes. These responses are strongly influenced, particularly by alterations in the water storage capacity. Some coastal ecosystems, such as mangroves and coral reefs, regulate the intensity of natural hazards, reducing the damage caused by hurricanes or storm surges.

Cultural services are the non-material benefits people obtain from ecosystems through spiritual enrichment; cognitive development – reflection, recreation, inspiration and aesthetic experiences; social relations; and educational and cultural heritage values.

Supporting services are necessary for the production of all other ecosystem services and differ from provisioning, regulating and cultural services in that their impacts on people are often indirect or occur over a very long period of time. Some of these services, such as erosion regulation, can be categorized as both a supporting and a regulating service, depending on the timescale and immediacy of their impact on people. Supporting services include soil formation, photosynthesis, primary production and nutrient recycling. Water is recycled through ecosystems, carrying nutrients and energy; providing an essential environmental component for all living organisms; and playing a crucial role in the majority of ecological processes.

Ecosystem services and the natural environment

Throughout history, people have benefited immensely from sound ecosystems, but they have also worked to protect themselves from a range of far from benign natural environmental conditions. However, the term "natural" has come to imply "clean and safe" to many people, particularly in developed countries. The natural environment can be divided into two types, pristine or wild – not altered by human activities, or modified to human requirements to allow improved quality of life and economic well-being. In order to understand environmental sustainability, the extent to which the environment can be maintained in its pristine wild form has to be addressed from the human security perspective. This will enable ecosystem services to be obtained without a cost and deal with the issue in a balanced manner. Therefore, when discussing ecosystem services, the term "natural" implies "nurtured" and not nature in its wild form. Some of the health services provided by ecosystems are good examples of the ambiguity presented through the classic dichotomy between "natural" and "nurtured".[21]

From a human security perspective, some of the natural hazards in the wild, pristine environment can be:

- Heat, cold, rain, snow, wind and related natural disasters;
- Constant search for sufficient food, water and shelter;

- Infections caused by insects and parasites that spread from person to person or animal to person through air, food or water;
- Dust, damp, wood smoke, pollen and other airborne hazards; and,
- Injuries from falls, fires and animal attacks.

Even though the environment in its pristine condition induces natural hazards, it is obvious that ecosystems provide enormous benefit to us, as stated above. It is, therefore, important to keep a balance by appropriately maintaining the environment, so that humans can be protected from natural hazards induced by the pristine condition, and at the same time, ecosystem services can be maximized. This balance is the key to attempting environmental sustainability.

2.4 Environmental degradation and development imperatives

One of the main objectives of IFM is preservation of environment. However, flood management policies are not designed in isolation. Being part of overall sustainable development, they have to be appropriately placed within the development matrix. It is, therefore, important to clearly understand the various drivers of development as well as environmental degradation.

Drivers of environmental degradation

Drivers of environmental degradation differ from country to country depending on the given socio-economic setting. In general, however, they can be traced to poverty and consumerism, agricultural development, industrialization, urbanization, transportation, tourism and population growth. Throughout history, such drivers are, ironically, manifested in activities designed to improve livelihoods and economic welfare.

Poverty and consumerism Poverty is the biggest polluter. In order to preserve the natural environment, poverty has to be tackled up front. Feedback links between poverty and environment are extremely complex.[22] Inequality in modern societies may foster unsustainable behaviour because the poor rely on natural resources more than the rich, and have no real prospects of gaining access to other types of resources. The rich on the other hand, with their consumptive behaviour exploit natural resources. These impacts are felt globally. In turn, depleted natural resources and degraded environments can accelerate the process of impoverishment, as the poor are deprived of natural assets.

Agricultural development In the absence of other livelihood options, agriculture is the main activity in many regions of the world. By its very nature, agriculture is an intrusion upon, and a disruption of the natural environment, as human activities replace natural ecosystems (e.g. flood plains, forests or wetlands) with artificial ones. Direct impacts of agricultural development on the environment arise from farming activities, which contribute to soil erosion, loss of fertility, land salinization, alkalization, waterlogging, pesticide pollution and consequent deterioration of surface and groundwater quality.

Industrialization Since the dawn of industrialization, and until recently, most manufacturing technologies have placed a heavy toll on the environment, especially through intensive use of resources and energy, and through contributing toxic wastes (pollution). This is reflected in the depletion of natural resources (fossil fuel, minerals, timber, etc.), contamination of water, air and

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Urban flooding in Bangladesh

land, and overall degradation of natural ecosystems. Large quantities of industrial and hazardous wastes, created by the chemical industry, have compounded the waste management problem with serious environmental health implications.

Urbanization Industrialization, in turn, has led to widespread urbanization. This has been exacerbated by the lack of opportunities for gainful employment in rural areas, resulting in an ever-increasing migration of the poor to towns and cities, giving rise to emerging mega cities and sprawling urban slums. Rapid and unplanned expansion of cities in developing countries has resulted in degradation of the urban environment, and has widened the gap between demand and supply of infrastructural services, such as energy, housing, transport, communication, education, water supply and sewerage, and recreational amenities. This results in undesirable land use changes, a growing deterioration in air and water quality, and generation of wastes, all of which contribute to degradation of the urban environment.

Transportation Establishment of transport systems requires construction and maintenance of roads and rail embankments, navigation channels in rivers, ports and harbours, etc. Keeping river channels navigable requires changes in flow regimes. The road and rail bridges across rivers, if not designed properly, obstruct natural hydraulic processes. Further, transport systems have a wide variety of effects on the environment, such as air pollution, noise from road traffic and oil spills from marine shipping.

Tourism Tourism is crucial in many countries for economic development. However, due to pollution and solid waste disposal in natural water systems there is increasing stress on flora and fauna as their habitats are degraded by tourism activities, particularly in coastal ecosystems and small islands. Whether intentional or not, tourists and tourism can cause great damage to basic ecosystems.[23]

Population growth Population growth can accelerate all of the above impacts of environmental degradation. It causes accelerated consumption of limited resources, generation of pollutants, increased pressure on land, etc. Increasing population densities in floodplain areas necessitates huge infrastructure investment to protect people, their livelihoods and property from flooding. Flood and water resources management works, such as dams and reservoirs, weirs and embankments, are built to meet these needs. However, if such measures are not designed appropriately, they can lead to significant impacts on the environment.

2.5 In brief …

It should be recognized that, within river systems, flooding is the natural way for the system to discharge the water arising from occasional large rainfall events.[24] There is no problem until people decide to use these natural flood plains for socio-economic activities, and realize that protection against inundation is needed. This presents the dilemma of protecting against a natural hazard for the benefit of people who have chosen to live and work in floodplain areas.[25] However, disaster mitigation by restricting the occupation of flood plains limits the potential of these areas for socio-economic development.[26] Most poverty alleviation measures for development and improvement of livelihoods and human security, e.g. industrialization, agriculture, flood control and protection works, etc., are drivers of environmental and ecosystem degradation. Accordingly, flood management policies and practices have to be viewed within the overall matrix of drivers of environmental degradation. It is, therefore, extremely important to balance development imperatives: flood risks, their relation to social and economic vulnerability and sustainable development vis-à-vis the preservation of ecosystems.

How ecosystems are interlinked with flow regimes is discussed in Chapter 4. Impacts of flood management measures on the environment are discussed in Chapter 5.

Table 1. Principles of IFM and the ecosystem approach		
Ecosystem approach	**Integrated Flood Management**	**Potential consequences of not adopting IFM**
Resource management objectives are a matter of societal choices.	• Based on risk management principles. • Addresses building resilience in vulnerable societies. • Economic analysis is based on multi-criteria analysis, which factors societal values.	• Vulnerability and exposure to floods in local communities can be increased.
Management should be decentralized to the lowest appropriate level.	• Based on the importance of a participatory approach. • Appropriate mix of bottom-up and top-down approaches. • Integration of institutional synergy.	• Key legitimate interests are likely to be excluded from flood and water management decision-making, leading to adverse impacts upon some sectors of society and economy.
Ecosystem managers should consider the effects (actual or potential) of their activities on adjacent and other ecosystems.	• Aims at improving the functioning of a river basin as a whole. • Considers gains, losses and certainties arising from changes in interactions between the water and land environment. • Balances development requirements and flood losses and environmental needs.	• Inadequate consideration of the environment can lead to environmental degradation, which may have adverse impacts on the economy and society.
Recognizing potential gains from management, there is usually a need to understand and manage the ecosystem in an economic context.	• Adopts a best mix of strategies in line with factors such as the climate, basin characteristics and socio-economic conditions. • Aims at maximizing efficient use of flood plains while minimizing loss of life due to flooding. • Adopts ecosystem valuation in cost-benefit analysis.	• Change of land use and ecosystems can alter the natural regime of rivers, which may lead to loss of potential opportunities for sustainable use of water resources.
Safeguarding ecosystem structure and function in order to maintain ecosystem services should be a priority.	• Aims at environmental sustainability and maintaining fluvial ecosystem services and biodiversity. • Addresses human security concerns and losses due to flooding.	• Loss of environmental sustainability and ecological integrity caused by inadequate flood management reduces services potentially provided by ecosystems to society.
Ecosystems must be managed within the limits of their functioning.	• Addresses trade-offs between competing interests in a basin, in order to maximize the benefits and maintain environmental sustainability.	• Unless ecosystem functioning is addressed appropriately, opportunities to reduce the costs of flooding and to obtain benefits provided by ecosystems would be lost.
The ecosystem approach should be undertaken through appropriate spatial and temporal scales.	• The river basin or catchment as a whole is the planning unit. • The water cycle is treated in its entirety (including extreme events). • Working with both short- and long-term objectives and measures.	• Decisions in one sector for water management without linking knowledge from other disciplines and involving stakeholders is likely to affect negatively sustainable use of flood plains, including ecosystem services.
Recognizing the varying temporal scales and lag-effects that characterize ecosystem processes, objectives for ecosystem management should be set for the long term.	• Building upon the long-term uses of flood plains.	• Ad hoc approaches aimed at short-term benefits are likely to bring future ineffectiveness and greater than necessary negative impacts on the economy.
Change is inevitable and therefore management must have an adaptive approach.	• Adopts multi-faceted approach, with a mix of options, appropriate to the given conditions. • Adaptive management approach evaluates the impacts at regular intervals.	• One narrow approach dealing only with scientific facts cannot deal with uncertainty, which may lead to serious environmental deterioration in the future.
The ecosystem approach should seek the appropriate balance between, and integration of, conservation and use of biological diversity.	• Balances flood risks and preservation of ecosystem services for supporting livelihoods.	• Ignoring environmental considerations can have negative impacts on livelihoods, which may have serious health impacts. • Little consideration to flood risks can increase economic and human loss.
The ecosystem approach should consider all forms of relevant information, including scientific and indigenous and local knowledge, innovations and practices.	• Hydrological and engineering knowledge; social, legal, economic and environmental knowledge, data and information; indigenous knowledge of resources, adaptabilities, vulnerabilities and risks. • Mechanisms for cooperation of flood managers with intersectoral links.	• Poor knowledge of the hydrological cycle and its interaction with ecosystems can increase vulnerabilities in water resources use and increase flooding risks.
The ecosystem approach should involve all relevant sectors of society and scientific disciplines.	• Seeks to take a multidisciplinary approach with a broad range of actors from various communities and interest groups in the river basin.	• Mono-disciplinary approach cannot foresee negative consequences of particular actions and thereby ends up simply transfering risks instead of reducing them.

3. UNDERSTANDING THE BASIC CONCEPTS OF THE MORPHOLOGY AND ECOLOGY OF RIVERS AND THEIR FLOOD PLAINS

Knowledge of basic concepts about the morphology (landforms) and ecology (distribution of organisms and ecosystem processes) in rivers and their associated flood plains, and how morphological and ecological processes are driven by the flow regime, is fundamental to an integrated flood management approach. It requires understanding of the environmental impacts of flood management measures and exploring environmentally sensitive designs for new projects, or for mitigating the adverse impacts of previous works. This chapter describes the basic concepts of the morphology and ecology of rivers and their flood plains, to enable easy understanding of the processes that determine the behaviour of rivers as well as the ecosystems associated with floods and flood plains. In the following section, essentially, we address issues related to the middle and lower reaches of alluvial rivers, which exhibit floodplain development, and where river-floodplain processes are decoupled from the adjacent hill slopes. We also assume, for simplicity and understanding, that there are no water quality problems due to anthropogenic pollution. Most of the concepts would also hold for other, less common channel types.

3.1 Fluvial processes and flood plains

Floods are generally generated by heavy rainfall events or by melting snow (or a combination of both) and, as such, flooding is a natural process. River channels are naturally adjusted to contain average-sized flows. Therefore, every couple of years, higher flows that exceed the channel capacity are expected to occur, allowing water to flow over the banks and inundate the adjacent

YIN HEXIAN

Meandering of the Yellow River, China

lands. In addition, flooding may result from direct rainfall onto the flood plain or rising groundwater levels. Flooding is simply a part of the natural variation of hydrological processes. Flooding plays a key role in determining the level of biological productivity and diversity of flood plains. It contributes to soil fertility, to habitat formation and turnover, to exchange of nutrients and organisms, etc.

Fluvial processes

Headwater streams and upper reaches, that can be termed upland valleys, usually have strong linkages with the adjacent hill slopes. On the other hand, middle and lower reaches normally show floodplain development and are thus decoupled from their hill slopes.[27] In these reaches, the processes determining the riverine landforms are mostly dependent on the upstream drainage catchment, where the water and sediment that flow through the reaches are generated.

At a longer timescale, the independent drivers in a given river basin are its geology and climate. The local temperature and rainfall regimes weather the exposed rocks, determining the character of the soil and the type of vegetation that can grow across the basin (see Figure 2). Together, acting through the stream network, all of these variables prescribe the discharge, sediment and wood debris regimes at the catchment's outlet.

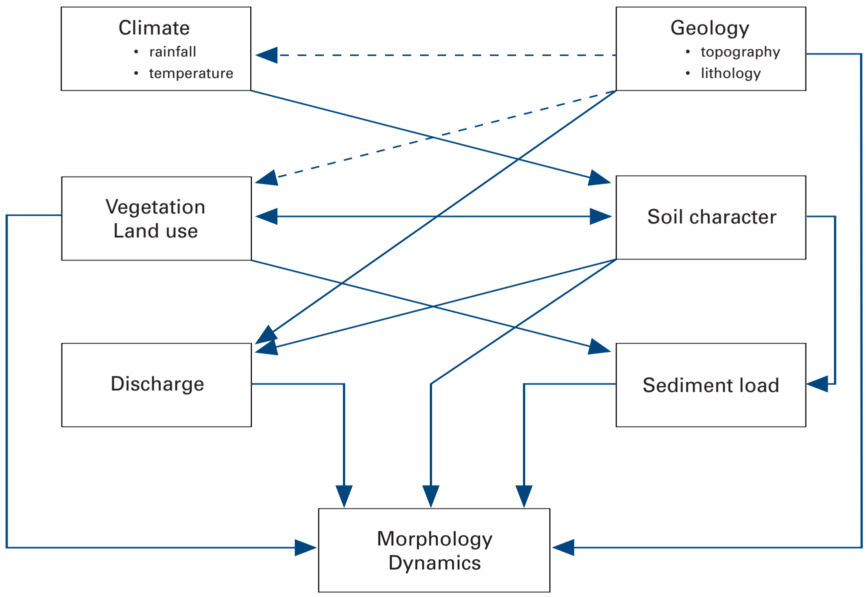


Figure 2. The fluvial system[28]

Flood plains

It is important to understand the term "flood plain", and it is useful to refer to Figure 3 – organization of floodplain components and processes at a spatio-temporal hierarchy. Region A represents the flood plain flooded every year and extends up to a kilometre for large rivers. Point bars and recently cut-off meanders form the essential part of the region, which is typically characterized by herbaceous vegetation and early successional tree species. River ecologists tend to define flood plains as "areas that are periodically inundated (usually annually) by lateral overflow of rivers or lakes, or by direct precipitation or even by a rise in groundwater levels",[29] and lay emphasis on the responses of the biota to the resulting physico-chemical environment.

Region B refers to the primary and secondary floodplain succession associated with medium frequency of floods and extends to about 10 kilometres. It constitutes natural levees and oxbow lakes and is characterized by early successional woodland. However, these geomorphic and vegetation units extend to regions C and D. Region C is associated with high magnitude/low frequency of floods and can extend tens of thousands of kilometres in large river systems. Engineering hydrologists, more concerned with the economic consequences of flooding, use a normative definition based on hydraulics, i.e. "the area on both banks of a river inundated by a flood event with a recurrence interval of 100 years".[30]

Region D is associated with climate and base-level change and is influenced by postglacial relaxation on hydrological and sediment inputs to flood plains. Fluvial geomorphologists, on the other hand, define a flood plain as a "largely horizontal alluvial landform adjacent to a river channel, separated from it by banks, constructed from sediment by the river in the present climate and flow regime, and overflowed during moderate flow events".[31,32]

Flood plains are highly heterogeneous ecosystems. Although broadly flat, the floodplain microtopography presents a complex assemblage of small channels, depressions, backwaters, hillocks and ridges. Depressions within flood plains are particularly important wetlands, both for

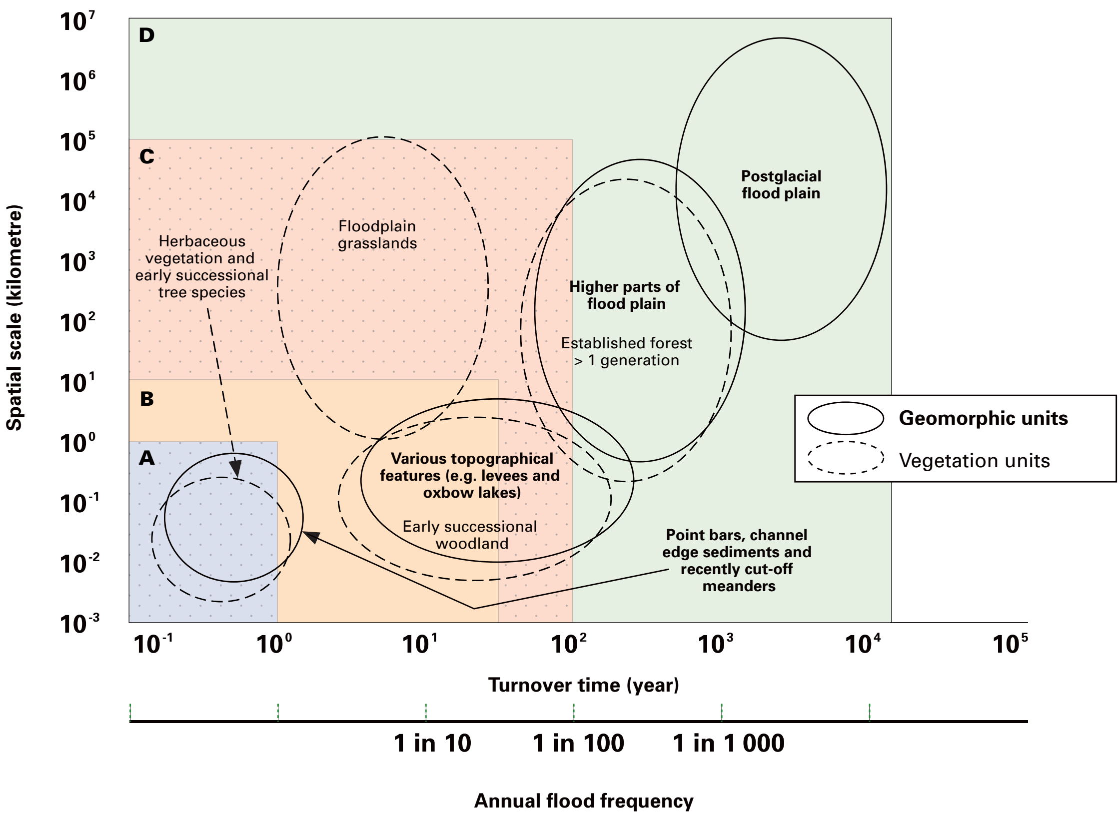


Figure 3. The organization of floodplain components and processes as a spatio-temporal hierarchy[33,34]

biodiversity and for livelihood support (agriculture, fishing and livestock production). These depression wetlands are often connected to the river by small channels, which bring flood water and associated fine sediment and nutrients, and allow migration of fish, which spawn and breed on the flood plain. Such wetlands may retain flood water after the river level has dropped. As the water level slowly falls, flood recession agriculture is practised. Some depressions support particularly important ecosystems, such as floodplain forests, which provide habitats for large populations of birds.

In this publication, the term "river corridor" is used to indicate the area consisting of the stream channel and its associated flood plain. The extent of a flood plain gets defined by the specific geomorphic and vegetation characteristics (as discussed in preceding paragraphs) and the objectives of floodplain management. As such the river corridor has semi-permeable lateral boundaries with the adjacent terrestrial ecosystem and with the underlying groundwater system.

3.2 Morphological regime

Most river systems have non-alluvial bedrock and laterally constrained reaches in their headwaters, as well as at selected locations along their course. Where not constrained laterally by valley walls, all alluvial rivers form sediment bars and build a flood plain. For a given valley slope, river landscape is determined by the interactions among the hydrological regime (the pattern of flow variability), the sediment load and calibre,[35] the coarse woody debris regime, the bed and bank materials and the floodplain vegetation. Thus, the water, sediment and large woody debris entering an alluvial reach interact among themselves and with the reach materials and vegetation, modifying the movable sediment boundary through erosion and deposition, creating a range of channel styles or patterns. Depending on its stream power or energy (a function of discharge, channel width and slope), sediment size and the effects of riverine vegetation, an alluvial channel and its associated flood plain will show meandering, anastomosing, single-thread sinuous, wandering or braided

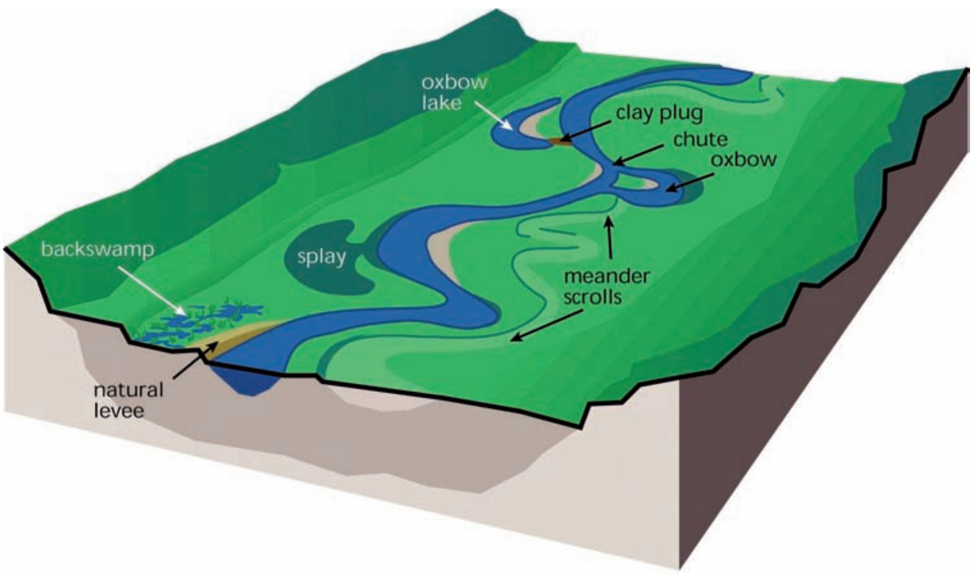


Figure 4. Landforms and deposits of a meandering riverine flood plain[36]

patterns. There are clear relationships between river type or pattern, and some important ecological indications of ecosystem health, such as habitat complexity and biodiversity. A river corridor ecosystem encompasses much more than just the wetted part of the main channel. It also includes all secondary channels, sediment bars, river islands and the flood plain itself.

Rivers of different styles and patterns inevitably move around over time and create their flood plains through different mechanisms. However, the specific mechanisms of floodplain formation and the rates, at which such floodplain formation takes place, can vary considerably. For example, meandering rivers migrate laterally by eroding the existing floodplain material on the outer side of bends and at the same time depositing sediment on the point bar formed on the inner side, a process known as lateral accretion. Wandering gravel-bed rivers, on the other hand, create mid-channel sediment bars, which can be colonized by vegetation. During high discharges, the vegetation traps fine sediment, thus raising the surface of the bar by vertical accretion, until it becomes an established island, which later becomes part of the flood plain when the river abandons one of its adjacent side channels. Morphologically, a river can thus be considered to be in a state of dynamic equilibrium: the configuration of the landform is continuously changing, but the overall composition remains the same (shifting habitat steady state concept). Figure 4 shows such an alluvial river corridor, in this case for a stream with a meandering pattern. In this manner, the fluvial processes of erosion and sedimentation, driven by flooding, sediment transport, woody deposition and vegetation growth, continuously modify the entire river corridor, even though, from a distance, the landscape might seem unchanged.

Under natural conditions, or due to human-induced land use changes, the erosion rates in some drainage basins cause sediment to be delivered to a river well in excess of the river's ability to transport it downstream. As a result, these fluvial systems are inherently unstable, continuously raising their bed levels in a process known as aggradation. The resulting flood plains, which in some cases are huge alluvial fans, can be very wide, and the frequent channel shifts can cover large distances laterally. In extreme cases, such rivers are known as "hanging" rivers. If embanked, to avoid flooding and lateral avulsions, aggradations continue within the narrowed channel, raising the bed levels to higher elevations than the surrounding flood plains (see Figure 5). Flood and environmental management in such rivers obviously present some daunting challenges.

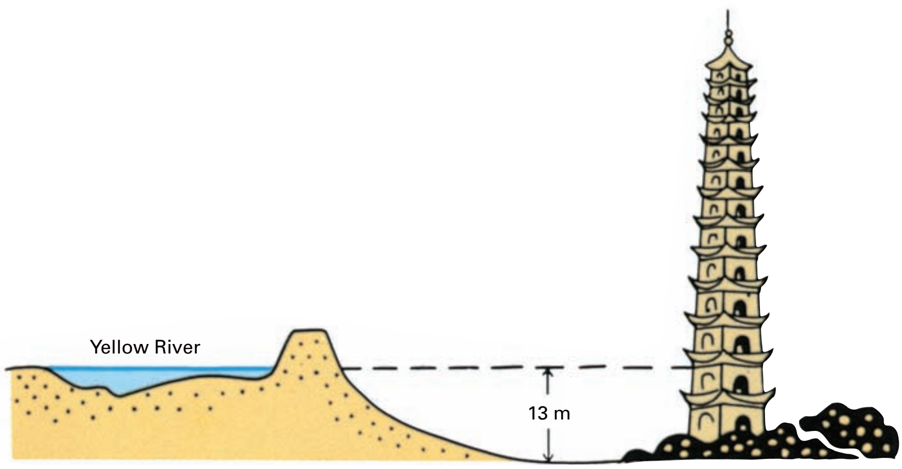


Figure 5. Sketch map of the "hanging river" near Kaifeng[37]

On the other hand, dam construction, soil protection and reforestation, which decrease sediment loads, or changes that result in increased flood flows, can also alter the river equilibrium but in the opposite way. The excess transport capacity may result in a lowering of the riverbed, a process called degradation. Severe degradation results in locally decreased flooding risk, but the exported bed material can cause aggradations farther downstream. Degradation also causes serious environmental change along a river corridor, including loss of riverine vegetation due to lowering of the groundwater table, etc.

3.3 Biological diversity

Healthy and diverse ecosystems provide important goods and services as important foundations for many aspects of economic and social development. Most of the services provided by riverine ecosystems result from the biological activity of the diverse assemblages of organisms found within those systems. The importance of maintaining biological diversity (also referred to as biodiversity), therefore, goes far beyond mere protection of endangered species and beautiful wetlands. It is necessary to obtain a thorough understanding of how aquatic and terrestrial ecosystems function and interact, in particular in relation to flood management interventions.

For organisms to survive, the following conditions have to be met:

- Water of adequate quality: a series of different physical and chemical variables such as dissolved oxygen, pH, temperature, etc., must range within allowable limits, and there must not be excess pollution;
- Availability of appropriate quantity and variability of water, to support natural biological processes; and
- Availability of diverse physical habitats.

Indeed, it is widely accepted that riverine biodiversity and productivity are to a large extent governed by physical variables relating to the flow, sediment and temperature regimes. In order to survive, grow and reproduce, organisms need food and a place to live – a habitat – within the physical environment they inhabit. Not only are these requirements particular to each species, but different life stages of a given species (for example, a brown trout egg, juvenile and adult) can have very different dietary and habitat needs, and a certain landscape must supply them all if that species is to persist there.

Natural river corridor habitats are highly diverse. Diversity in a reach depends on how the habitat changes in space and time.

The spatial heterogeneity is determined by whether the habitat is: in deep or shallow water; in sunny or shaded areas; on flat mud or sand or gravel; with or without aquatic vegetation; in a fast or slow current; in clear or turbid water; in small rivers or large rivers; in a spring brook or main channel, etc.

The temporal variability is provided by: alternation of low and high flow conditions (e.g. floods); seasonal changes between warm and cold water; single or multiple channels contracted and expanded into the flood plain, etc.

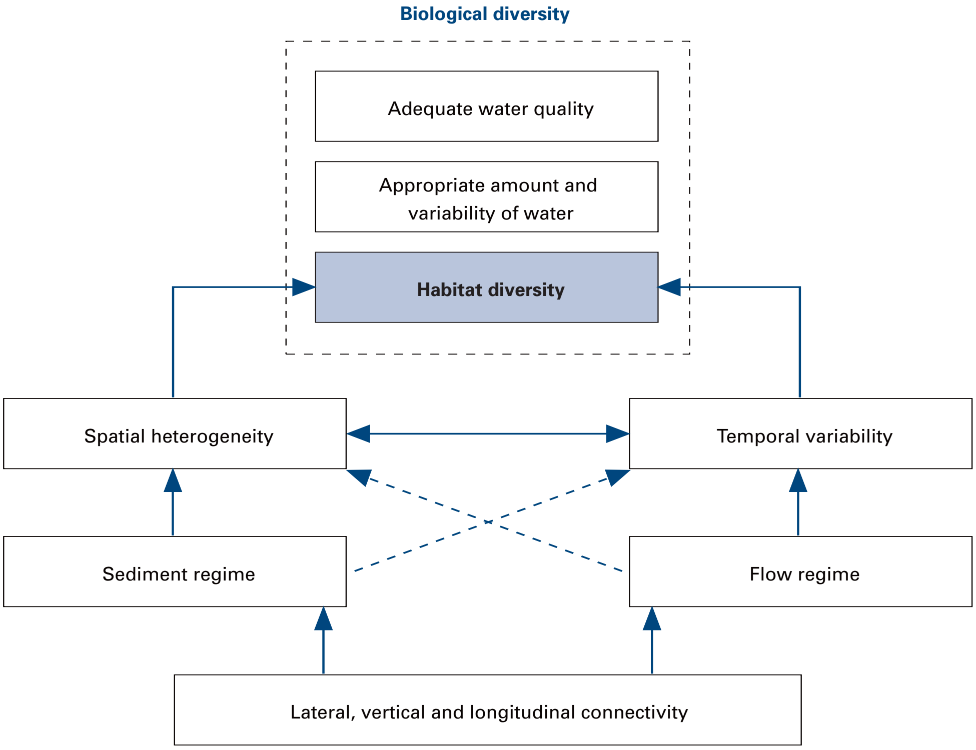


Figure 6. Various components in formulating biological diversity

This explains why diverse and complex environments are able to sustain a higher variety of organisms than uniform ones. In general, the higher the habitat complexity in a river corridor, the greater the biodiversity that it can sustain. Figure 6 shows various components that support biodiversity. Shifting habitats, created by disturbances, are essential components of a healthy river ecosystem.

In high-energy fluvial systems, which have steep slopes and/or high floods in relation to their sediment load and calibre, the disturbance pattern, i.e., the rate at which habitats are created and destroyed, may be too fast to maintain high biodiversity. A typical example is gravel and sand-bed braided rivers, where bars and islands have such a high turnover rate that most of the in-channel habitat patches are relatively recent. However, they provide habitats for very specific and often highly endangered fauna and flora characteristics for early successional stages. On the other hand, a low-energy meandering river, which migrates laterally at a slow rate, might have a large proportion of its flood plain under mature vegetation, with little availability of young patches. Such a system will also be too homogeneous to sustain a large biodiversity. Indeed, it has been shown that biodiversity is maximized in ecosystems with an intermediate turnover rate.[38] In other words, too much change – continuously resetting the system, or too little change – allowing one type of habitat to dominate, results in decreased diversity.

Most of the species have varying requirements during their life cycles, but also at different times of the day or the year. This implies that organisms need to be able to move between different habitat patches. These movements can happen once in a lifetime, across long distances, as is

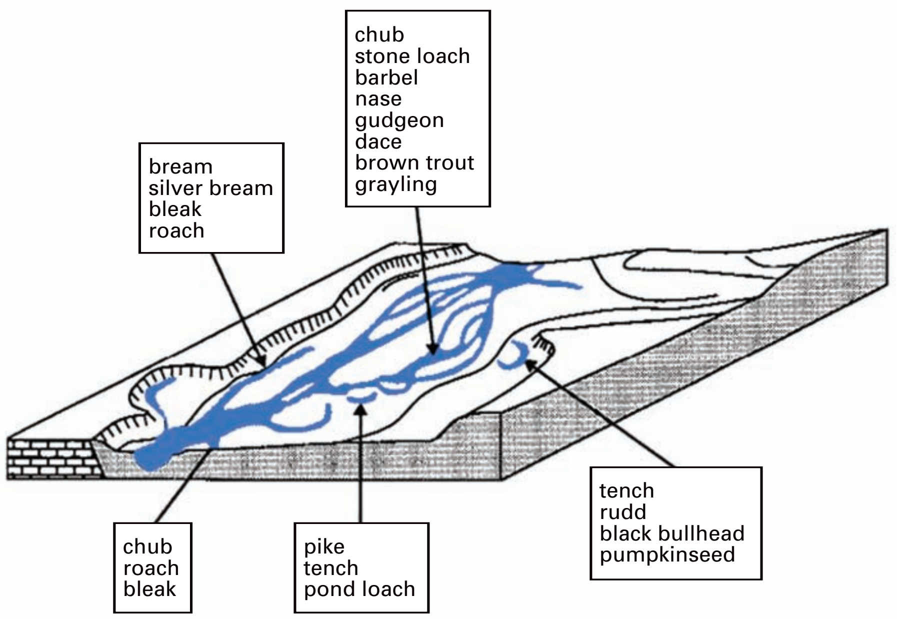


Figure 7. Use of spawning habitat by different fish species in the Upper Rhône[39]

the case with some species of salmon migrating from the ocean towards headwaters, or can occur on a daily basis, for example, when an individual switches between feeding and resting positions. Movement can take place along the river axis or transversally, where some fish species use lateral habitats to spawn, but later return to the main channel. Many species have patchy spatial distributions, with few individuals per population. Movement between patches requires intact lateral and longitudinal connectivity, so that such species can sustain their ecological processes.

Traditional flood control schemes tend to oversimplify the river corridor, resulting in a spatially homogeneous ecosystem, which is not able to supply varied habitat features for a diverse range of species. For example, the alluvial reach shown in Figure 7 presents a variety of aquatic environments, used for spawning by a wide range of fish species. If a reach like this is channelized for navigation or for flood control, concentrating flows in a single channel thereby cutting off the others, it ends up as a uniformly narrow, single-thread, deep channel, with much reduced heterogeneity. Many habitats are lost in the lateral channels and in the flood plain, resulting in a sharp decrease in local, and finally in regional, biodiversity.

3.4 Morphological and ecological connectivity

Section 3.3 stressed the importance of maintaining the connectivity, i.e., the measure of how spatially continuous a river corridor or a matrix is.[40] Connectivity of various habitats is important for fulfilling the needs of organisms to move about the landscape and for sustaining a series of physical, biological and chemical processes that control the structure and functioning of the river corridor.

Based on these concepts, river corridors are understood as three-dimensional systems that change in time (Figure 8). Longitudinally, the upstream catchment is linked to the downstream reaches. This link is mostly seen as uni-directional, down-slope fluxes of water, sediment, organic matter (for example, wood and leaves) and solutes. However, many organisms, both aquatic and terrestrial, use the river corridor to move both up- and downstream. Dams and weirs, or the occurrence of reaches that cease surface flow, can interrupt the connectivity along the longitudinal dimension of a river, impeding migrations or retaining sediments and large woody debris, which have an important morphological and ecological role. It needs to be noted that some rivers are naturally intermittent or ephemeral. In such case, dewatering of some reaches, and the subsequent loss of connectivity, are natural disturbances that control ecosystem structure, together with the flood regime.

As shown above, seasonal inundation of the flood plain is essential for maintaining river corridor characteristics. Flow regulation and the construction of embankments decrease the lateral connectivity, restricting the movement of organisms and the fluxes of food, sediment, organic silt, etc., between the channel and its flood plain. For example, consider surface water spilling onto the flood plain during a high discharge period, i.e., flood waters overflowing the main channel and spreading over part of the flood plain. Because larger flood events are less common, the areas immediately adjacent to the main channel are inundated frequently, whereas those farther away are flooded only temporarily, once every couple of years, and have less heterogeneous structures. The flooding not only allows aquatic organisms to move out of or into the main channel, but also causes morphological change, creates new habitats, deposits part of its fine sediment load (including fertile organic silt), sustains wetlands, renews floodplain ponds, and temporarily stores water on the flood plain, alleviating flooding downstream, etc. If flows in such a reach were regulated, the connection between the main channel and the flood plain would be weakened and most of these processes would be curtailed.

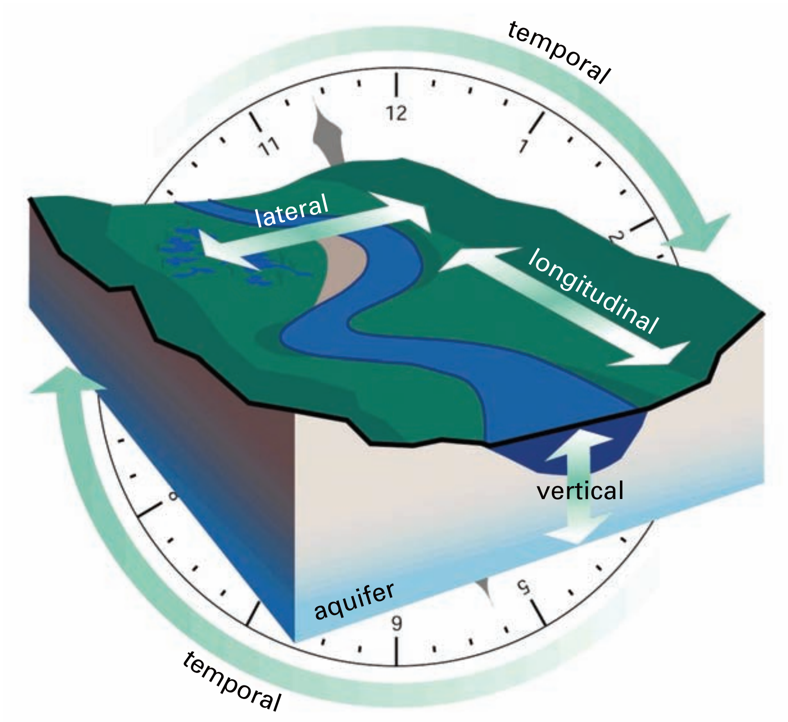


Figure 8. Spatial and temporal dimensions of a stream corridor[41]

The vertical connectivity is associated with the connection between the surface system and the underlying alluvial groundwater system, the so-called hyporheic zone. Intact vertical connectivity, i.e., surface-groundwater interactions, is important because underground microbial processes sustain river corridor productivity and help maintain water quality. Also, many floodplain wetlands and ponds, as well as most riparian trees, are dependent on groundwater. In addition, upwelling groundwater provides important cold water refugia for many species.

The variety of water bodies and the enormous complexity of the flow paths within an alluvial river corridor, with main and secondary channels, sedimentary deposits of all textures and shapes, ponds, fringing wetlands, etc., among which water flows perennially or episodically, at the surface, subsurface or in the aquifer, under shade or exposed to solar radiation, etc., result in a large variability of temperature regimes, superimposed upon the shifting physical habitat mosaic. In other words, the river morphology as well as the habitat availability are most likely in a state of regime or dynamic equilibrium, where the configuration of individual patches is continuously changing, but the overall availability of different habitat types remains more or less the same over a reach. This conceptual model of the regime functioning of a river corridor is known as the "shifting habitat mosaic steady state concept".

It is, therefore, fundamental to understand that habitat diversity and connectivity are not fixed in space and time, but are continuously created and destroyed by the river dynamics. If a highly diverse river corridor is not allowed to change, e.g. by preventing the occurrence of floods or by separating the flood plain from the main channel by embankments, then new habitat patches will stop being created, and the system will become homogeneous, as the existing vegetation stands mature and take over the originally heterogeneous fluvial landscape.

3.5 In brief …

The main principles relating to the ecology of alluvial rivers and their flood plains can be summarized as follows:

- Rivers continuously change, migrating across their floodplain belt. The flow, sediment and large wood regimes, interacting with bed and bank materials and with the riverine vegetation thus create and destroy fluvial features.
- The dynamic, shifting mosaic of in-channel and floodplain habitat patches is a fundamental attribute of river systems, providing space for many different riverine species of plants and animals, which have evolved to thrive in this dynamic and heterogeneous environment.
- In order to support natural ecological processes, riverine habitats require three environmental conditions to be fulfilled simultaneously: water of adequate quality; availability of appropriate quantity and spatial and temporal variability of water; and availability of diverse physical habitats.
- The connections along the river corridor, both in the longitudinal, lateral, and vertical directions, are fundamental, both for riverine organisms and the functioning of the river ecosystem.
- A strongly modified flood regime (i.e., changes in magnitude, timing and frequency of floods) may adversely impact the ecosystems. It is relevant to maintain the structure and function of fluvial ecosystems because most of the ecosystem services provided by river corridors depend on these, and are lost when rivers are simplified.

4. FLOOD PROCESSES AND ECOSYSTEM SERVICES: INTERRELATIONSHIPS

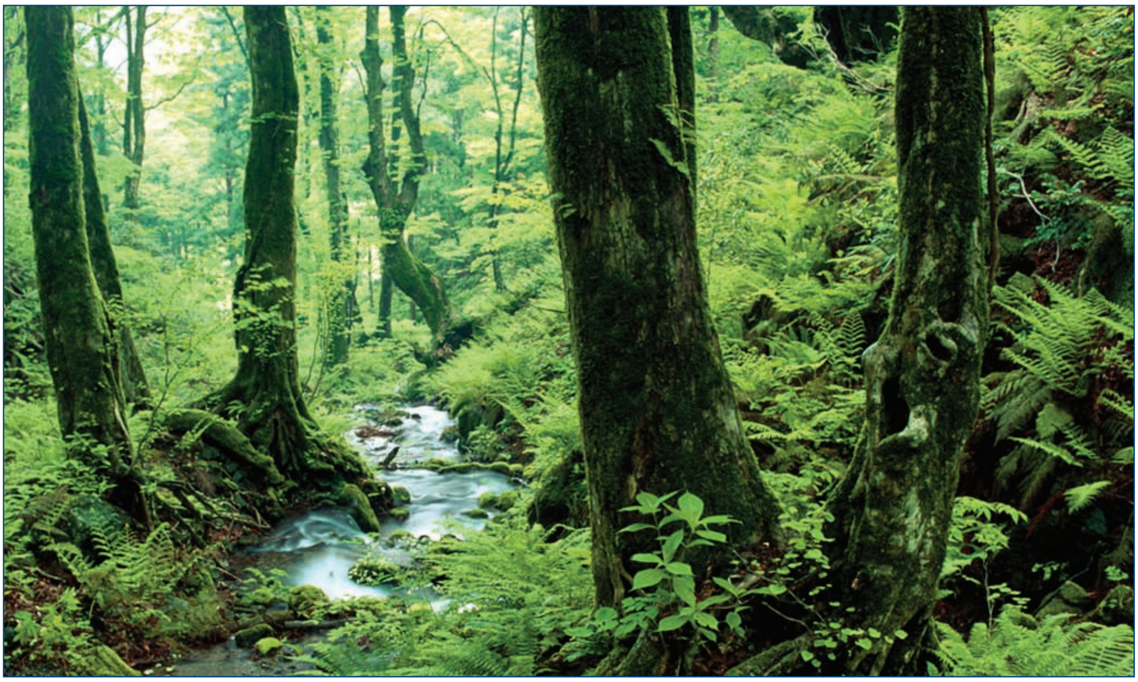
Ecosystems play a vital role in determining the hydrological response of a river basin. It is, therefore, important to understand the various hydrological processes generating floods, and how ecosystems interact with such processes to influence the volume, magnitude and timing of flood events. This chapter therefore discusses the roles of various ecosystems (e.g. forests, lakes and ponds, wetlands, river corridors, estuarine and coastal ecosystems) in the hydrological processes and response and how these systems interact with flood events. It also discusses the potentials and limitations of ecosystems in providing flood moderation (see Table 2 for summary).

4.1 Forests

Forests are terrestrial ecosystems tied to processes within the soil. The ability of the soil to support vegetation depends on their characteristics: physical (organic matter, water holding capacity, structure and bulk density); chemical (types of mineral elements present); biological (diversity and activity of microorganisms present); and the local microclimate (temperature, precipitation and evaporation demand).

Forests as a vital source of energy for people and aquatic ecosystems

Riparian forests serve as interfaces between terrestrial and aquatic ecosystems[42] and provide varied and essential habitats for the local riparian species. A continuous forest offers transport routes for arboreal animals (animals that live in trees). Forest resources directly contribute to the livelihoods of people, and nourish agriculture and food supplies, and thus constitute a major source



WMO

of national wealth.[43] They help maintain water quality by filtering nutrients and other pollutants from the subsurface and groundwater flow paths, and by retaining sediment from surface flows. By providing shade to floodplain ponds, sloughs, spring brooks and river channels, they regulate the thermal regime. They supply allochthonous[44] organic matter to the aquatic system, in the form of leaves, twigs, large woody debris, etc., which provide critical food resources for aquatic organisms.[45] In tropical regions, they moderate the harsh hot climate and provide a host of products such as wood, crops, nuts, pasture, etc.

Forests and hydrological processes

Forests play an important role in determining hydrological processes in the basin by seasonally stabilizing river flows through their complex structure, fostering infiltration and evapo-transpiration. Through infiltration, they support groundwater recharge, which is slowly released over a prolonged period. Under given hydro-climatic conditions, they can reduce the total water yield from the catchment due to higher evapo-transpiration. During prolonged droughts, river discharge can drastically decline. These effects, however, are yet to be quantified even at the local scale due to extremely complex processes.[46] The regulating effects of forests have certain limitations and depend mostly on structural complexity, the size and types of forests, in combination with depth and structure of soil cover and the antecedent soil moisture conditions in the catchment. Extreme flood events, in terms of flood peaks, are however, not influenced by the absence or presence of forest cover, as continued precipitation can saturate the soil leading to enhanced surface runoff.

Riparian forests interact with the flow hydraulics, thereby influencing the river corridor morphology, strengthening bank resistance to scour, and narrowing and deepening channels. In the lower reaches with wide flood plains, vegetation roughness results in larger depths; the resulting excess storage helps in slowing down the flood wave and attenuates the flood peaks in the downstream reaches. Driftwood and floating logs may jam the waterways of cross-drainage works and cause obstacles to flood flows resulting in a rise in water levels upstream and possible levee-breach or bank overflows.

Forests and sediment supply to the river

Tree roots play an important role in determining the stability of slopes. They increase soil strength by helping it to resist tension, but at the same time they contribute their own weight to the loading. The pressures to convert forest and pasture lands to cultivation, along with legal and illegal logging, are continuously affecting forest cover. Absence of forest cover not only contributes to shallow landslides (whereby large areas of land lose part of their fertile topsoil), but also to gully erosion, resulting in land degradation and higher sediment discharges from catchments. Deep-seated landslides are, however, not noticeably influenced by the presence or absence of forest cover, as they are mostly influenced by geological, topographical and climatic factors.[47]

As mentioned earlier, inter-relations between hydrological processes and forest dynamics have not yet been investigated at the large catchment scale, mainly due to the complexity of the processes involved. Therefore, there is a critical need to initiate and strengthen long-term eco-hydrological monitoring of the influence of forests on dry season flows, flood mitigation and groundwater recharge in large catchments.

4.2 Ponds and lakes

Ponds and lakes are generally lentic water bodies,[48] i.e., non-flowing freshwater ecosystems. Water usually enters these bodies through direct precipitation, from tributary and distributed surface runoff, or from shallow aquifers. Water is lost from lentic systems through free surface evaporation, transpiration, transmission and outflow from the channel outlet. Oxbow lakes, created after a meandering river cuts off and abandons a meander, are not strictly lentic, as they become flowing systems during high flow periods.

Biological diversity of lakes and ponds

The biological diversity of lakes and ponds depends on their physical characteristics and their nutrient or atrophic[49] status. Biodiversity peaks near the shallow shores. Nutrients and sediments enter the lake from non-point sources. Driven mainly by solar and wind energy, temperature variations within these water bodies are very important in determining their ecological characteristics. In shallow and small water bodies, herein referred to as ponds, water temperature is uniform along the depth as sunlight easily penetrates down to the bottom. Differences in water temperature in deep-water bodies, herein referred to as lakes, forms thermal layers as heat energy does not penetrate the depths, and cooler water stays put near the bottom. The wind stresses that act at the lake surface supply the mixing energy that decreases sharply with depth. In lakes connected to river systems, the location and characteristics of the tributaries and the outlet also determine the extent of mixing in the lake. Whether a lake is mixed or stratified is critically important to its ecological characteristics.

Lakes and ponds provide a variety of human services, including drinking water supply, fishing, irrigation, recreation and livelihoods (e.g. agriculture, fishing, livestock production, etc.). These water

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Lake Léman on the Rhône River

bodies also provide vital services for the natural environment, such as assimilating plant nutrients, retaining sediments and recharging groundwater. They are rich in plant varieties and are the main life support mechanism for many plant and animal species, as well as migratory birds.[50]

Lakes and floods

The ability of these water bodies to store water helps them to attenuate flood peaks. A pond or lake intercepts overland flow and retains it until its storage capacity is full, before it starts overflowing and contributing again to the runoff. When a flood wave enters a lake, it is not transmitted directly to its outlet, but gets partly absorbed within the water body as the water level rises. Thus, when the maximum outflow is reached, there is also a large volume of stored water, which flows out with a time lag depending on the outlet characteristics, thereby attenuating flood peaks and slowing down their transmission downstream. The extent to which ponds and lakes play a role in flood alleviation during an extreme flood event depends on their type, location, the surface area, shape of the water body, the antecedent conditions and the hydraulic behaviour of the outlet.

4.3 Wetlands

Wetlands are defined as areas of marsh, fen, peatland or water; whether natural or artificial; permanent or temporary; with water that is static or flowing, fresh, brackish or saline, including areas of marine water, the depth of which at low tide does not exceed 6 metres.[51] They form transitional lands between fully terrestrial and aquatic systems. They may be tidal and non tidal, or, lotic and lentic. Although marine and coastal wetlands as well as lakes and pond are defined as wetlands herein, they are not discussed under this section but dealt with separately. The presence of surface water and the development of moist-soil vegetation are two characteristics essential for a habitat to be wetlands.

Geomorphic settings

Wetlands within different geomorphic settings tend to have different dominant sources of water and different hydro-periods, both of which influence the types of organisms that are adapted to live there. Some of the alluvial wetlands are closely connected with river channels while others are isolated. For example, depression wetlands (i.e. without surface outflow) often have strong groundwater connections with other wetlands and aquatic bodies. Some are essential amphibian habitats because seasonal dry out eliminates potential fish predators. Other common geomorphic settings include riverine, or river marginal, wetlands that include portions of alluvial flood plains and river deltas, lacustrine[52] wetlands notable for the narrow fringes that they occupy in sheltered lakeshores and reservoirs, and slope wetlands fed largely by groundwater discharging at topographic breaks. Each of the geomorphic settings supports wetlands in climates ranging from arid to humid.

Wetlands are often characterized by dense vegetation that is adapted to periodic inundation and desiccation. The water quality of wetlands is highly influenced by the associated aquatic ecosystem, soil, and type and amount of emergent vegetation. Wet flats that occupy topographically flat

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areas, however, are restricted to climates that are humid enough to support wetland vegetation and soils without groundwater or surface water sources. In some cases, they have accumulated enough organic matter to result in peatlands, known also as organic-soil flats. Wetlands are increasingly coming under development pressure and those with similar geomorphic settings are subjected to the same types of human alterations.[53]

Biological diversity of wetlands

Some wetlands, which are closely connected with the river by small channels, allow transport of and retain flood water, associated fine sediment and nutrients. The high rates of nutrient retention in wetlands enable them to produce large quantities of biomass, which again forms the base for both aquatic and terrestrial food webs. Wetlands are very important ecosystems and they provide critical habitats for many species[54] and support livelihoods. Hence the biodiversity of wetlands in terms of the range of species they support can be extraordinarily high. Temporary flooding is of critical importance in maintaining the functioning of wetland ecosystems.

Wetlands support both aquatic and terrestrial species and the prolonged presence of water creates conditions favouring specially adapted plants (hydrophytes). Wetlands are shallow and slow moving or standing water environments. They provide favourable habitat for many species, and importantly, are suitable breeding and nursery areas for fish, and nesting and nursery areas for birds. Floodplain wetlands have ecological linkages that can extend for thousands of miles (migratory birds, anadromous fish etc).

Wetlands and hydrological cycle

Wetlands have significant influence on the hydrological cycle (see Box 1). Hydrological processes are influenced by the storage capacity for water, the transmission loss from a wetland to an aquifer or the recharge capacity of the groundwater. Flood attenuation is one of the most important wetland functions. This flood attenuation service occurs primarily on large flood plains in the lower

Box 1. Wetlands and the hydrological cycle

A study conducted at the Centre for Ecology and Hydrology, Wallingford, UK, based on 439 published statements on the water quantity functions of wetlands from 169 studies worldwide concluded:
- Wetlands are significant in altering the water cycle;
- Most wetlands in flood plains reduce or delay floods, but not always. In fact, more than one-third of headwater wetlands increase flood peaks;
- Wetlands evaporate more water than other types of land and therefore in two-thirds of cases, they reduce average annual river flows;
- In two-thirds of the wetlands, the flow of water in downstream rivers is reduced during dry periods;
- Some floodplain wetlands on sandy soils recharge groundwater when flooded. But most wetlands exist because they overlie impermeable soils or rocks and there is little interaction with groundwater.

Source: Bullock, A. and Acreman, M., 2003. The role of wetlands in the hydrological cycle, *Hydrology and Earth System Sciences*, 7 (3): 358–389.

reaches of river basins where over bank flood water is stored in large hollows and depressions. Additionally, the flood wave is slowed and reduced by resistance caused by the roughness of the wetland vegetation, thus delaying and reducing floods downstream.

As wetlands encompass a wide range of ecosystems including bogs, fens, mud flats and flood plains, it should be recognized that not all wetlands perform flood attenuation to the same degree. The importance of wetlands in reducing downstream flooding increases with wetland area, size of the flood, closeness to an upstream wetland, and with the lack of other upstream storage areas. Clearly, flood attenuation only takes place if the storage is not full at the time the flood impinges. In wetlands that are saturated, little storage may be available for subsequent floods.

4.4 River corridors

A river is dynamic: it migrates, cutting in some places and filling in others, thereby creating new channels. It is constantly creating and destroying riverine habitats. A river corridor (channel plus flood plain and all landforms within it) is seen as a shifting mosaic of landforms, in dynamic equilibrium or regime: constantly changing but always "looking the same". This requires a continuity of flows and sediment regime. Various components of the flow regime regulate ecological processes in running water ecosystems: the magnitude, frequency, duration, timing and rate of change of hydrologic conditions. Floods form an important component of the flow regime of any river system, as larger flows are instrumental in erosion and subsequent deposition processes. The flooding needs to occur at the right time of year, because the life cycles of native species are adapted to such natural river regimes.

Different species (or life stages of the same species) require a suite of habitats created by such a shifting mosaic of landforms at different times of the life cycle. For natural riverine ecosystems to flourish a river needs space to create complex habitats. A higher diversity of landforms, and thus of habitats, is observed in rivers which are free to move about. If flows are regulated and maintained at uniform and lower values, because of power generation or flood control measures, rivers lose spawning habitats, resulting in a loss of ecological integrity, i.e., there is an impoverishment in the biodiversity and the ecological functioning of the riverine ecosystem.

Depending on the distance of an ecosystem from the river channel, it forms part of the shifting mosaic, as presented in Figure 4. When locating embankments, the specific characteristics of the river corridor need to be considered.

Flood plains as the pressure release valve of floods

The flow in rivers that are confined between embankments has greater power because the velocities are higher than if the river were allowed to spread out onto the flood plain. This stream power can result in destructive bank erosion and channel changes that are more severe than if the river was able to overflow its banks. The ability of a river to overflow onto its flood plain during high flow events prevents building up of this destructive stream power. Flood plains as such serve as a kind of "pressure release valve".[55] The flood plains store the spilled water and attenuate the flood peaks downstream while recharging the groundwater.

Diffusion of pollutants

Floods can create environmental problems and create risks if precautions are not taken to minimize the spread of pollution due to flooding. Sewage backs up into basements and untreated sewage from treatment plants located in flooded areas can cause health hazards during flooding. This issue is of great concern in urban areas in developing countries, where untreated sewage is disposed into open drainage systems. In addition, wastewater contains microbial pathogens, suspended solids, toxics, nutrients, trash and other pollutants and can contaminate drinking water sources.

WWF, 2004

Kafue Flats in the Kafue River, Zambia

Flood waters have potential to spread industrial as well as domestic chemicals. The location of dangerous chemicals should be carefully planned on the basis of knowledge of the flood plain and flooding mechanisms. Chemical stores or factories on flood plains may suffer leaks or damage to installations, thereby resulting in the spread of these chemicals and oil spills through flood waters. Such contamination can have long-term impacts on the health and habitability of the flooded area. It takes concerted effort, time and financial resources to clean up such environmental pollution. During the clean-up process, disposal of chemicals is an important decision, and should be taken with great care, as this has the potential to affect recipient ecosystems.

4.5 Estuarine and coastal ecosystems

Estuary and deltaic processes

River flows are the main source of fresh water, sediment, nutrients and silica for estuaries. The level of river inflow determines the sediment load that is delivered to the estuary. Floods deliver proportionately greater sediment loads than ordinary river flow, and form an important part in determining the hydrological regime of rivers that in turn play an important part in shaping the estuary morphology.[56]

A river carries sediment to the coast and deposits it beyond its mouth. Tidal currents and waves rework the newly deposited sediments, affecting the shape and form of the resulting structure. A river delta results from the interaction of fluvial and marine forces in the vicinity of the river mouth.[57] The long-term evolution of a deltaic plain becomes a function of the rate of riverine sediment input and the rate and pattern of sediment reworking, transport and deposition by marine

YIN HEXIAN

Delta region of the Yellow River, China

processes after the initial deposition. Thus, a flow regime in fluvial systems influences the morphological processes of coastal zones. Structural flood control works, such as dams and diversion works, alter the flow regime and consequent sediment supply to coastal areas, thereby heavily influencing the morphological and ecological processes of these areas.

Characteristics of coastal ecosystems

Water flow, through and across catchment soils, transports dissolved and suspended nutrients to the estuary downstream. Nutrient rich fresh waters from the catchment mix with highly oxygenated waters from the ocean, making estuary and deltaic areas the most biologically productive regions of the marine environment. Thus coastal freshwater and brackish habitats are determined by the character of the freshwater input into the system – quantity, quality and timing – and the daily and seasonal influence of tides, causing changes in salinity, temperature, turbidity and energy flux. Such coastal ecosystems include mangroves, beach forests and peat swamps (tidal and floodplain forests) that contain considerable biological diversity. Coastal ecosystems provide valuable resources, habitat, subsistence and livelihood to forest dwellers, thereby supplying the means to hold these communities together. The socio-economic importance of these areas is especially evident in the more arid regions of developing countries. The seasonal ebb and floods determine the lifestyle and agricultural practices of communities dependent on these ecosystems.

Coastal ecosystems as buffers against flooding

Low-lying coastal areas in the tropics frequently experience coastal flooding caused by cyclonic storms, storm surges and tsunamis, as well as tidal flooding. Saltwater penetrates into deltaic watercourses and may flood low-lying delta lands. Coastal ecosystems protect inundation of inlands along the estuaries and coastal areas, through their physical presence and capacity to retain water and absorb the energy of coastal storms. For example, as widely reported in the Indian Ocean tsunami (2004), extensive areas of mangroves can reduce the loss of life and damage caused by tsunamis by taking the first brunt of the impact and by dissipating the energy of the wave as it passes through the mangrove area. On the other hand, narrow strips of mangroves, when uprooted or snapped off at mid-trunk and swept inland, can cause extensive property damage and loss of life. Despite many examples of the positive role played by mangroves and other coastal forests in mitigating the effects of tsunamis and other natural disasters, there is, unfortunately, still insufficient information available to determine to what extent and under which circumstances mangroves and coastal forests might provide an effective mitigation against natural disasters.[58]

Synergizing coastal and fluvial systems

As discussed above, coastal morpho-dynamics and ecosystems are influenced by flow regime in the fluvial systems. Many coastal ecosystems are under severe threat from water development activities including flood management projects and potential rise in sea level due to potential climate change. This "coastal squeeze" severely restricts the size and width of coastal wetlands and thus their adaptive capacity.[59] In delta areas, over allocation and storage of available water in the upstream part of basins, without taking account of the environmental needs of the

Box 2. Integrated Coastal Zone Management

What is ICZM?
Integrated Coastal Zone Management (ICZM) is a planning and coordinating process which deals with development management and coastal resources, and which is focused on the land/water interface.

Objectives
The overall objective of ICZM is to provide for sustainable use of coastal natural resources and for maintenance of biodiversity. Environmentally planned development is reputed to add to economic and social prosperity of a coastal community in the long term. Fisheries productivity, increased tourism revenues, sustained mangrove forestry and security from natural hazard devastation are among the practical benefits of ICZM.

Principles
- The coastal area is a unique resource system that requires special management and planning approaches;
- Water is the major integrating force in coastal resource systems;
- It is essential that land and sea uses be planned and managed in common;
- The edge of the sea is the focal point of coastal management programmes;
- Coastal management boundaries should be issue-based and adaptive;
- A major emphasis of coastal resources management is to conserve common property resources;
- Prevention of damage from natural hazards and conservation of natural resources should be combined in ICZM programmes;
- All levels of government within a country must be involved in coastal management and planning;
- The nature-synchronous approach to development is especially appropriate for coastal areas;
- Special forms of economics and social benefit evaluation and public participation are used in coastal management programmes;
- Conservation for sustainable use is a major goal of coastal resources management;
- Multiple-use management is appropriate for most coastal resource systems;
- Multi-sector involvement is essential to the sustainable use of coastal resources;
- Traditional resource management should be respected;
- The environmental impact assessment approach is essential to effective coastal management.

Source: Clark, J.R.,1992. *Integrated management of coastal zones*, FAO Fisheries Technical Paper No. 327, FAO.

morpho-dynamic processes of deltas, coastal ecosystems and mangrove swamps, threaten their survival. Protection of coastal ecosystems lies in synergizing IWRM, and IFM as its subset, with Integrated Coastal Zone Management (ICZM) (see Box 2).

4.6 In brief …

- Forests play an important role in determining hydrological processes in the basin by seasonally stabilizing river flows. Extreme flood events, in terms of peak flow and total volume of runoff are, however, not influenced by the absence or presence of forest cover.
- Tree roots play an important role in slope stability. Shallow landslides may occur due to the loss of forest cover and contribute large sediment volumes into river channels.
- Ponds and lakes play an important role in attenuating flood peaks and delaying their occurrence, due to their water storage capacity, which again depends on type, location, surface area, shape of the water body, its antecedent conditions, and the hydraulic characteristics of its outlet.

- Wetlands have a significant influence on the processes of the hydrological cycle through storage of water, transfer of water to an aquifer or recharge of groundwater. But not all wetlands attenuate floods to the same degree.
- Different species in river corridors require a variety of habitats provided within the shifting mosaic of landforms created by the natural flow and sediment regimes of the river.
- Flooding has the potential to spread pollutants and various chemicals stored on the flood plain to larger areas thus affecting human and ecosystem health.
- Floods are an important component of the flow regime of any river system. They are the main source of fresh water, sediment, nutrients and silica for estuaries. Thus, the flow regime of the fluvial systems influences the morphological and ecological processes of coastal areas.
- The environmental needs of the morpho-dynamic processes of coastal systems, deltas and coastal ecosystems are influenced by fluvial systems. Coastal ecosystems protect against inundation inland, along the estuaries and coastal areas, through their physical presence and capacity to retain water and absorb the energy of coastal storms.

Table 2. Ecosystems and flood processes

	Upper reaches	Middle reaches	Lower reaches	Estuaries and deltas
Forests	+ Regulate hydrological processes through increased infiltration and transpiration + Increased infiltration reduces runoff against short duration and low intensity storms + Soil stabilization helps reduce landslides depending on geographical, topographical and climate factors + Provide thermal regulation to the waters	+ Forests alongside the river channel can increase bank resistance because of their binding effect + Narrow and deepen river channel to maintain water levels for a given flow + Help reduce shallow landslides and consequent high sediment concentration in streams	+ Retard flood waves due to roughness of the floodplain vegetation	
	- Flood regulating effect depends on size, soil structure and antecedent conditions - Flood regulating effect may not be appreciable in extreme events	- Vegetation in the river channel can increase flow resistance and increase water levels - Log jams, in narrow waterways can further decrease their carrying capacity, thereby increasing water levels upstream - Flood regulating effect may not be efficient in extreme events	- Log jams in narrow waterways can further decrease their carrying capacity, thereby increasing water levels upstream	
Ponds and lakes	+ Decrease overland flows and/or moderate flood peaks downstream by first storing flood water and then slowly releasing it with a time lag	+ Decrease overland flows and/or moderate flood peaks downstream by first storing flood water and then slowly releasing it with a time lag + Trap sediments + Recharge the groundwater	+ Decrease overland flows and/or moderate flood peaks downstream by first storing flood water and then slowly releasing it with a time lag + Trap sediments + Recharge the groundwater	
	- Flood regulating effect depends on type, location, storage volume, surface area, shape of the water body and the hydraulic behaviour of its outlet	- Flood regulating effect depends on location, storage volume, surface area, shape of the water body and the hydraulic behaviour of the outlet	- Flood regulating effect depends on location, storage volume, surface area, shape of the water body and the hydraulic behaviour of the outlet	
Wetlands		+ Decrease flood peaks downstream by first storing flood water in depressions and then letting it flow out slowly with a time lag + Retard flood waves, due to roughness of the vegetation	+ Decrease flood peaks downstream by first storing flood water in depressions and then letting it flow out slowly with a time lag + Retard flood waves, due to roughness of the vegetation	
	- When saturated, headwater river margin wetlands generate runoff, accentuating flood peaks	- Flood regulating effect depends on type, antecedent conditions, location, size of the depression and its connectivity to river flows	- Flood regulating effect depends on type, antecedent conditions, location, size of the depression and its connectivity to river flows	

Table 2 *(continued)*

	Upper reaches	Middle reaches	Lower reaches	Estuaries and deltas
River corridors		+ Ability of a river to overflow onto its flood plain helps moderate bank erosion in downstream reaches + Attenuate and slow flood waves by storage and roughness of the floodplain vegetation + Recharge groundwater	+ Ability of a river to overflow onto its flood plain helps moderate flood peaks in downstream reaches + Attenuate and slow flood waves by storage and roughness of the floodplain vegetation + Recharge groundwater	
		- Allow rivers to change and meander, and allow floods to overflow onto flood plains making human settlement and gaining benefits from flooding difficult	- Allow rivers to change and meander, and allow floods to overflow onto flood plains making human settlement and gaining benefits from flooding difficult	
Estuarine and coastal ecosystems				+ Help stabilize their shoreline and thereby buffer against the actions of winds, waves and water currents + Absorb the energy of coastal storms, driven waves and storm surges, leading to protection of inland areas
				- Flood wave regulation effect – much depends on the size, location, types of the ecosystem

[ ] indicates that all the boxes need not necessarily be filled

[+] indicates the positive aspects of ecosystems on flood processes

[-] indicates the limitation and negative aspects as flood management service provider

5. FLOOD MANAGEMENT INTERVENTIONS AND ECOSYSTEMS

An integrated approach to flood management calls for a best mix of structural and non-structural measures. An isolated flood management option may achieve a certain objective, e.g. protection of a certain area, but cannot address the various objectives that should be addressed at the river basin level. The residual risks associated with structural solutions, for example due to uncertainty in the input information for analysis of these options or due to a series of chain failures of structural control and protection works, have to be taken into account. This chapter, therefore, looks at some of the environmental consequences of structural flood control and protection works such as dams, detention and retention basins, bypass channels, embankments, channelization, etc. The chapter looks at how these options affect the environment, especially in terms of flow regime, sediment transport, water quality and biodiversity. It also explores possible options to avoid, reduce or mitigate the negative consequences. Table 3 summarizes the impacts of structural flood management measures on various river corridor processes and possible mitigation measures for environmentally sound flood management. From an environmental perspective, it is important to recall the influence of non-structural measures on the environment. Some non-structural flood management measures are also discussed, particularly with respect to how they help in protecting the environment.

5.1 Dams and reservoirs

Sustainable management of a river as a resource requires that water is delivered at the time of need for human use and that the supply is reliable. At the same time, water should be available for the survival of the riverine ecosystems. Dams are constructed across valleys or rivers to store, regulate and divert water for various purposes such as agricultural production, hydropower generation, human and industrial use and flood peak attenuation. Most dams serve multiple purposes. Large areas along the river stream are submerged by the reservoir created behind the dam. In-stream regulating devices, such as weirs and locks, result in areas of permanent inundation within the main channel, thereby negating the normal ecological functions associated with flood events.

Flood control dams and their reservoirs

Flood control dams store all or a portion of the flood waters in the reservoir, particularly during peak floods, and then release the water slowly. Typically, the principal use of such dams is to store a portion of the flood volume, in order to delay and attenuate flood peaks downstream. Space within a reservoir is generally reserved to store impending floods. Based on hydrological forecasts, the reservoir is regulated in a way to minimize the chances of coincident peaks from floods in different tributaries synchronizing in the main stem of the river downstream. Small to medium floods generated from the catchment are fully captured by the reservoirs. However, extreme flood events are only partially attenuated and their transformation downstream is delayed. The extent of attenuation depends on the available storage capacity vis-à-vis the magnitude of the flood event. The main performance parameter in assessing the flood control benefits of a reservoir is, therefore, the extent of the flood peak reduction during extreme events.[60]

Many dams have multiple purposes and flood management may be required only for a few days or weeks in any particular year. Potential conflicts between flood management objectives (where storage space in the reservoir is required) and hydropower and irrigation (where it is desirable to keep the storage capacity as filled as possible) make it difficult to operate a multiple purpose reservoir. While allocating water for various uses, the need to maintain environmental flows[61] should also be addressed. This should not only be guided by the percentage of the total flows released, but also by the need for variability of outflows in the downstream of a storage reservoir to be mimicked in order to maintain near-pristine conditions (see Box 3).

Water quality

Storage of water in reservoirs alters the water quality. Large storage reservoirs tend to stratify, so that the water at the bottom is much cooler. Water released from such reservoirs, through outlets provided near the bottom, can result in significantly cooler temperatures downstream, to which native fish might not be adapted.[62] The impact can be stronger on aquatic invertebrates. Relatively constant flows can create constant temperatures, which affect those species that are dependent on temperature variations for reproduction or maturation. When streams are excessively dewatered, because of irrigation extraction or during periods with no power generation, the unnaturally low flows can warm more easily, thus holding less dissolved oxygen. In winter, on the other hand, such streams can become too cold and sometimes freeze.

In reservoirs, anaerobic (methane-producing) processes and algal populations tend to dominate if there is an excess of nutrients (organic matter, nitrogen and phosphorus) in the water and sediment. Eutrophication (resulting in excessive algal growth and de-oxygenation of the water) may

Box 3. Environmental flows

"Environmental flows" is an easy concept. It means enough water is left in our rivers; this is managed to ensure downstream environmental, social and economic benefits.

An environmental flow is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. A distinction may be made between the amount of water needed to maintain an ecosystem in close-to-pristine condition, and that which might eventually be allocated to it, following a process of environmental, social and economic assessment. The latter is referred to as the "environmental flow", and it will be a flow that maintains the ecosystem in a less than pristine condition.

In order to define water requirements, one should:

- Make an informed societal choice on water allocations;
- Carry out environmental flow assessments as part of river basin planning; and
- Implement environmental flows through active or restrictive flow management.

It is also important to recognize that there is no single best method, approach or framework to determine and realize the environmental flows with new or existing infrastructure. New dams provide opportunities to implement environmental flows. This may require creating a policy and legal framework and sufficient means for covering the costs of measures required to be taken through incentives and disincentives.

Source: Dyson, M., Bergkamp, G. and Scanlon, J., 2003. *Flow – The Essentials of Environmental Flows*, IUCN The World Convention Union, Gland, Switzerland and Cambridge, UK.

Kerr Dam on the Flathead River, USA

occur in such reservoirs. The process is supported by the lack of mixing and oxygen transfer in standing water. In warmer climates, reservoirs with increased eutrophication can suffer from toxic algal blooms, the excessive growth of aquatic plants such as water hyacinth and the production of methane.

Sediment and organic material

Dams also disrupt the natural flow of sediments and organic materials. As stream flow slackens in the reservoir, the sediment transport decreases and suspended sediment along with the organic material, which provides vital nutrients for downstream food webs, also drops out and is lost to the downstream ecosystem. The organic silt is mostly retained in the reservoir, instead of fertilizing the downstream flood plains, estuarine and coastal ecosystems. The elimination or reduction of high flood events changes the structure and functioning of the downstream flood-plain ecosystems. As the river remains within its channel for long periods of time, the lateral connectivity between the river channel and their fringing wetlands is lost.

The availability of resources to the food chain downstream is affected in various ways. The reservoir exports plankton and algae in the flow releases. On the other hand, there is a lack of organic matter such as wood and leaves, which are retained in the reservoir. In most cases, the turbidity of downstream water is decreased below a reservoir, which may lead to increased primary productivity in the reach. Algal growth may occur in the channel immediately downstream from dams because of the nutrient loading of the reservoir releases. With a decrease in flood magnitudes downstream of a dam, there is an invasion of new varieties of plants into the river sand bars and islands, resulting in reduced conveyance capacity of the river during flooding.

Sediment-depleted water released from dams can erode finer sediments from the receiving channel, thereby scouring the downstream streambed and banks until the equilibrium bed load is re-established. It may also result in coarsening of the streambed which, in turn, reduces habitat availability for many aquatic species living in or using interstitial spaces. Without new sources of sediment, sand and gravel bars alongside and within streams are eventually lost, along with the habitats and species they support. In addition, as the stream channel becomes incised, the water table underlying the riparian zone also lowers, thereby affecting the composition of vegetative communities within the stream corridor.

Longitudinal connectivity

River-dwelling species have various migratory patterns. Anadromous fish, such as salmon, migrate up rivers to spawn and the young descend to the sea. On the other hand, catadromous fish, such as eels, move downstream to lay eggs, while their young move upstream. Dams can impede or hinder the passage of fish, invertebrates and certain terrestrial animals, thereby interrupting the longitudinal connectivity along the river corridor. Native fish populations are particularly affected as river species reliant on the natural flow regime disappear downstream of the dam.

Reservoir operations

A change in the timing, frequency and magnitude of natural floods can have negative impacts on both terrestrial and aquatic habitats. Their effects on the physical habitat and biological diversity are not understood well. Therefore, dam design and reservoir operations play a special role in maintaining various natural processes in the river. For ecological reasons, the time of release of flushing flows should preferably coincide with biological requirements and/or historical periods of high flow, since the biota is adapted to such a regime. The managed flood releases can help maintain these natural processes and their downstream floodplain wetland ecosystems and their dependent livelihoods. Using water stored in a reservoir for supporting a river corridor ecosystem depends on the ecological relationships that govern productivity and biodiversity within a catchment and the river flood plain. Understanding and modelling these relationships is arguably one of the greatest challenges for reservoir operations. Various steps in the planning, design and implementation phases of a project for managed flood releases are given in Box 4.

The decision on reservoir operations, setting the duration of the flow releases and the shape of the artificial flood hydrograph should form part of the project design and should be based on ecological requirements as above. It is also important to maintain or restore the natural seasonal temperature regime of released flows by using multiple and/or depth-selective intake structures; avoid sedimentation in the reservoir, as it can lead to accelerated riverbed degradation downstream of the dam; and allow passage for fish over weirs and dams, in both directions.

5.2 Embankments

Embankments (also referred to as levees or dykes in some countries) are constructed mainly from earth and used to confine stream flow within the specified area along the stream, or to prevent flooding due to sea waves or tides. Embankments should be resistant to hydrostatic pressure of floods, erosion, piping failure and seepage. Further, river protection works such as spurs, studs, revetments, etc., are attached in combination with embankments to fulfil those objectives. Since early times, embankments have played a vital role in protecting people on flood plains against frequent flooding and continue to be the most favoured flood management option.

Box 4. Guidelines for managed flood releases

The following 10 steps have been designed within a strategic approach to the planning, design and implementation phases of a project cycle. The order in which these steps are undertaken may vary depending on the circumstances surrounding the particular dam, reservoir or downstream flood plain or delta.

Planning
- Step 1: Define overall objectives for flood releases
- Step 2: Assess overall feasibility

Design
- Step 3: Develop full stakeholder involvement and technical expertise
- Step 4: Define links between floods and the ecosystem
- Step 5: Define flood release options
- Step 6: Assess impacts of flood options
- Step 7: Select the best flood option

Implementation
- Step 8: Design and build engineering structures
- Step 9: Make releases
- Step 10: Monitor, evaluate and adapt the release programme

Source: Pamphlet on *Managed Flood Releases; Reservoir operation to restore and maintain downstream wetland ecosystems and their dependent livelihoods*, Department for International Development, Centre for Ecology and Hydrology, Wallingford, UK.

Lateral connectivity

By containing flows within embankments, impeding seasonal floodplain inundation, the floodplain area exposed to inundation is restricted. This disrupts the lateral hydrological connectivity along the river corridor, with various effects on both the ecology of the channel and its flood plain. Further, embankments that are too close to the main channel decrease the natural heterogeneity of the flood plain, and impede the creation of new side channels and wetland areas. This reduction in habitat heterogeneity can dramatically impact fish populations, as many backwaters that were periodically connected to the main watercourse during the river floods no longer receive seasonal flows. These backwaters can be critical breeding and feeding areas for fish (see Figure 6).

Lack of floodplain inundation reduces transmission loss and groundwater recharge, thereby severely affecting the groundwater resources and their associated ecological and economic benefits. This has consequences on base flow-groundwater interactions, and degrades riverine habitats. Flood water spreading onto the flood plains improves soil fertility by depositing silt, exchanging nutrients and carbon between flood plain and channel, creating new habitats, and reinstating floodplain refuges and spawning areas for river species. Embankments reduce floodplain fertility because sediments and their nutrients are no longer deposited and exchanged.

Since embankments cannot guarantee absolute flood prevention, they can be designed to only provide a moderate level of protection. The degree of protection is generally driven by economic considerations. For example, it may be appropriate to protect agricultural lands against floods of a one-in-ten-year return period and allow them to be inundated during higher floods, thereby still

ZHANG ZAIHOU

Embankments in the Yellow River, China

maintaining the natural benefits of flooding (e.g. delivery of nutrient and organic rich sediments). Embankments that are designed for protecting urban and industrial areas need to be combined with bypass/diversion channels and/or detention/retention basins. There is a need to give due weight to the environmental impacts of construction of embankments, while making these design decisions.

Embankment spacing

When designing the alignment for new embankments, one should keep their likely adverse impacts in view. Particularly, efforts should be made to include floodplain water bodies such as ponds, wetlands, oxbow lakes etc., within the embankments, setting them as far apart and as far away from the main channel as feasible.

Typically, embankments result in steep-sided, trapezoidal, single channel cross-sections, rather than the more natural multiple channels with gentle bank slopes and flat-lying floodplain surfaces. By reducing the area that can be flooded, and by maintaining a larger proportion of the flow in the main channel with lower roughness, embankments decrease the travel times and increase flood peaks downstream. The high depth-to-width ratio of embanked channels makes them inherently unstable during high flows, requiring continuous maintenance.

Removing or setting back the embankments, in parts of the flood plains that are not intensively used for human development, can result in lower water levels and flow velocities, leading to larger in-channel storage and reducing flood peaks downstream. In certain situations where flood plains are used extensively for economic activities, this may not be a viable option. In such cases, a possible option for partly restoring the river-floodplain interaction is to set back the embankments, farther from the main channel thereby partially re-establishing the lateral connection with floodplain wetlands and backwaters and restoring the river's ability to move about. This also reduces the velocity of the stream, results in lower flood stages, and restores, in part, the natural functions of the flood plain, including temporary flood storage. A river corridor is an enormously complex system, which cannot be fabricated. A comprehensive integrated approach is, therefore, required to undertake removal of embankments including land use planning. Magnitude, frequency and characteristics of floods, geographical setting and socio-economic background of the region have to be taken into account in any given situation.

5.3 Detention and retention basins

Detention and retention basins are natural depressions or excavations, which can be used for temporarily storing flood water to reduce peak floods downstream. Detention basins are similar to retention basins except for the fact that the latter do not have controlled outlets. Detention basins hold the water temporarily and then slowly release it through a natural or man-made drainage channel, while water collected within retention basins slowly percolates into the ground or evaporates. According to the topography, the type and size of detention and retention basins can be different. They can be brought into operation at the desired stage of a flood wave, enabling reduction in flood peaks downstream. Often, natural depressions are also used for agricultural purposes.

Temporarily stored flood waters flow back into a natural drainage/river within a few days depending on the size of the basin, drainage capacity of the outflow and the need to keep space for subsequent flood waves. However, in the case of retention basins, flood waters may remain stored for days or months, as they can only be released through infiltration or evaporation. These basins generally do not alter the sediment and organic matter balance of the river. Their impacts on the natural flow regime of the river depend on their inflow characteristics and operation policy. When flood flows are detained for a few days only, there can be no important changes in water quality. However, if water is stored for long periods, the changes in water quality could be similar to those occurring in ponds, such as increased temperature, decreased dissolved oxygen (DO), eutrophication, etc.

These basins can be built to function as artificial wetlands or as permanent ponds, and thus help to create habitats for aquatic and semi-aquatic species. A useful option for environmentally sound flood management is to utilize gravel pits in or near flood plains, especially around large towns, as wetlands and ponds, thereby providing wildlife habitats, as well as serving recreational purposes. They can also play a valuable role in building awareness of the local population about flood risks as well as biodiversity, if they are designed and managed with these aims in mind.

In many countries in the monsoon regions of Asia, appropriately designed paddy agricultural fields can be used for the detention of flood waters, providing external benefits beyond their basic production function. Specifically, these multiple functions include flood alleviation and other forms of natural land conservation as well as the restoration of water resources.[63]

5.4 Bypass and diversion channels

Bypass channels divert river flows from a point upstream of an area requiring protection. These diverted flows can be discharged back to the same river, herein referred to as a bypass channel, or into another natural drainage system nearby, herein referred to as a diversion channel (see Figure 9). Flows into bypass and diversion channels are regulated by gates. Functioning of a bypass channel depends mainly on its location, length, carrying capacity and inlet characteristics.

While a bypass channel reduces flood magnitude in the bypassed area, it may increase flooding farther downstream, as flood waters are rushed through the bypass channel. A diversion channel can increase the possibility of flooding in the receiving drainage system downstream if the diverted flows are larger than its carrying capacity. Detention or retention basins, constructed in conjunction with the bypass system, can avoid such situations.

Impacts of bypass and diversion channels on sediment balance depend on whether or not the intake allows for bed load passage from the river into the bypass. If the bypass channel only draws flood waters from the river without carrying its share of bed load, increased sediment concentration in the bypassed reach of the river can induce deposition, therein leading to aggradation. Combined with the subsequent encroachment by riparian vegetation, this can potentially decrease the conveyance capacity in the bypassed reach. This can be avoided if the bypass channel is appropriately designed to draw its share of bed load from the river. This enables the bypassed reach to attain a new dynamic equilibrium under its new flow and sediment regimes, maintaining its ecological health. The same can be said in the case of a diversion channel after a new dynamic equilibrium is attained by the drainage system where the diversion channel is discharged.

However, if a bypass channel diverts flows at all stages, thereby affecting the low flows, habitats and vegetation in the bypassed reach of the river are likely to be affected. With reduced flows in the main stem of the river, streamside vegetation can encroach into the river channel, thereby changing its physical character. Such altered flow conditions often favour exotic species, which places greater survival pressures on native species. A bypass channel has no appreciable impact on the quality of the water in the river or diverted flood waters.

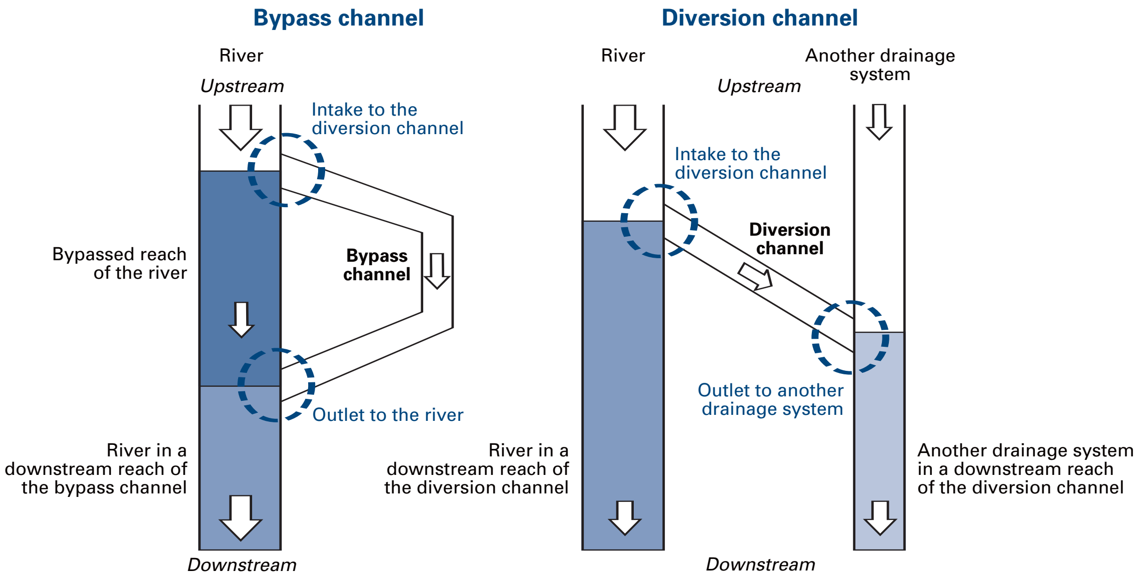

Figure 9. Bypass channel and diversion channel

5.5 Channelization

Channelization projects are undertaken in order to increase flow depths for navigation or/and reduce flooding, by increasing the overall conveyance capacity, reducing friction and confining the flows into one single channel. This can be accomplished by straightening, widening, deepening, realigning or/and revetting (lining) the channel. Large wood pieces embedded in the river bottom cause localized backwater that leads to sediment accumulation, bar creation and subsequent vegetative growth. Removal of such material considerably changes water flow and sediment deposition patterns and is used as a channelization technique.

Channelization simplifies the form of the channel and floodplain environment by straightening and homogenizing the channel and disconnecting it from side channel features. Channelized streams are not only straightened, which increases their slope, but their roughness is also decreased, which causes water to flow more rapidly and there is increased scour. The net effect is flood alleviation in one area at the expense of aggravated flooding in the reaches located farther downstream.

Channelization has negative consequences for the environment. The flood conveyance benefits of channelization are often offset by ecological losses resulting from increased velocities and reduced habitat diversity. Channelization eliminates bars and riffle and pool complexes needed at different times in the life cycle of certain aquatic organisms. In-stream modifications, such as a uniform cross-section and revetting, result in fewer habitats for organisms living in or on stream sediments. Hardening the banks of a river, through the use of rip-rap or concrete, can result in increased downward scour of the riverbed during high flows. In order to partly mitigate the

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Restored channel of the Itach River, Japan negative consequences, it is important to make use of techniques such as soft revetments, soil bioengineering, porous pavements, grassy swales, etc. Revetting and supporting river banks without the use of concrete (spiling, mattressing, the use of geo-textiles etc.) may partially preserve some functions of the fluvial ecosystem.

5.6 Non-structural measures

Structural measures can never completely eliminate the risk of flooding. Nevertheless, because of their physical presence, they have the potential to create a false sense of security, leading to inappropriate land use in the protected areas. Non-structural measures play an important role in reducing not only the catastrophic consequences of residual risks, but also adverse impacts on the environment. A comprehensive treatment of the non-structural measures is beyond the scope of this publication. This section, therefore, discusses some of the non-structural measures relevant to reducing negative impacts on the environment, and how they can help in protecting the environment.

Flood forecasting and warning

Of all the non-structural measures, flood forecasting and warning is the most widely accepted and has been used since the latter half of the 20th century. It supplements almost all other structural as well as non-structural measures. Flood forecasting involves estimating when a flood is likely to cause damage or loss of life, what its magnitude will be (usually in terms of its maximum stage at a given location) and how long it will last. Flood forecasts are formulated and issued with a certain lead time, allowing concerned authorities to take preventive and emergency measures. Authorities can respond appropriately with dam operations, opening and closing the gates of various flood management structures, anticipatory releases to increase reservoir storage capacity, etc. The effectiveness of a flood forecast and warning system is as much a function of the accuracy, timeliness and outreach of the forecast as of the response behaviour and preparedness. Inflow forecasts for reservoirs, detention basins, bypass channels, etc., play an important role in flood peak alleviation. It is important to draw reservoir operation guidelines covering various scenarios and effect managed flood releases based on these forecasts.

Land use regulations

Catchment management consists of interventions that affect the hydrological processes and includes introduction of suitable soil-protecting vegetation and crops, possible land use regulations, forestation, better forest management, controlling of shifting cultivation in conjunction with minor engineering works, e.g. check dams, trenches, contour bunds, etc. However, the impact of catchment management measures is limited to small floods, with decreasing effects for larger drainage basins. The most important contribution of catchment management is the reduction in the silt load contributed to rivers aggrading in nature.

Land use regulations play an important role in catchment management and in reducing the risk due to flooding. Land use change, particularly due to urbanization, has significant impacts on the magnitude and timing of floods in small catchments; it increases flood peaks due to reduced infiltration, reduces time of concentration and shortens flood duration. Regulating land use through building bylaws can help in preventing negative consequences due to urbanization or restricting development in such a manner that the hydrological response characteristics of the catchment are not changed.

The flood plain, as an integral part of the river corridor, offers possibilities for various economic activities. The harmful impacts of flooding can be reduced, through regulation and sometimes prohibition of certain activities and new development in high flood risk areas.[64] These can be in the form of land use bylaws, subdivision regulations, building codes, development policies and cost sharing through tax adjustments, etc. Location of industries producing or storing hazardous chemicals, sewage treatment plants and activities, such as storage of harmful chemicals that have potential to be dispersed due to flooding, should be regulated through such regulations. Flood risk maps form an essential prerequisite for land use regulations.

Managing the flood plain in a disciplined and environmentally sound manner requires a legal framework, especially where such a discipline needs to be enforced. In densely populated plains – with mostly landless people – equitable solutions are invariably opposed. In such situations, governments may struggle to curb encroachment by people. This is where a proactive legal regime, addressing both ecological and economic imperatives, is useful. Flood insurance, another non-structural measure, to a large extent, is complemented by a floodplain zoning programme.

Flood proofing

Where the extent of present development is substantial, alternate strategies such as flood proofing can be considered. Flood proofing, a combination of long-term, non-structural and minor structural measures, as well as emergency actions, is important not only in reducing damage due to flooding, but also in preventing the negative impacts on the environment such as the spread of pollutants. It includes provision of quick drainage facilities such as the cleaning of primary and secondary drainage channels and clogged cross-drainage works before the onset of the flooding season. Flood proofing measures include, among others, removing goods, equipment and harmful industrial, agricultural and domestic chemicals, beyond the area subject to flooding or out of contact with flood waters, by constructing high ground or small embankments. Existing facilities for drinking water supply have the potential to get contaminated. The sewerage disposal and treatment infrastructure located in the flood plains can cause nuisance and spread of diseases and pollution, affecting the health of the population. Provision should be made for the protection of such infrastructure.

Emergency preparedness, response and recovery

The most critical element in flood damage reduction is emergency preparedness and response. The awareness of the community at risk of flooding should be raised and maintained, with a clear understanding of their role in responding to emergency situations appropriately. This is critical in organizing coordinated evacuation from the affected area and maintaining healthy and hygienic conditions in the flooded areas. Information on evacuation routes, identified emergency shelters and other actions should be available, to all concerned, well in advance. Flood-prone populations should be dissuaded from storing harmful chemicals during the flood season, made aware of likely pollutants in flood waters and advised of the ways to avoid their adverse impacts. Actions undertaken during floods to prevent damage, such as diverting floods from sensitive areas, are generally known as flood fighting or flood combat. When flood control and protection works and other types of measures have either failed or have been insufficient to fully overcome the impact of flooding, these emergency measures become effective in mitigating flood impacts on society and environment.

After a flood, the cleaning operations are undertaken at an emergency level and little attention may be paid to the dumping of rubbish and debris. If not planned in advance, it may end up in drainage channels, ponds, wetlands or rivers, impacting the natural ecosystems. Recovery of drinking water supply, tube wells, sewerage systems and health infrastructure should be the priority. The spread of chemicals during floods can have catastrophic consequences on terrestrial ecosystems and requires earliest cleaning up. These cleaning operations require special attention in the post recovery phase to avoid long-term ill effects.

Living with floods

"Living with floods" – an age-old practice in many parts of Asia – recognizes that while it is not possible to completely eliminate floods, their negative impacts can be reduced through an understanding of flood risks, by working towards modifying this risk-generation process in a holistic manner and by minimizing settlement in areas subject to flooding. This strategy, in conjunction with non-structural measures such as land use planning, flood forecasting and warning and emergency planning, can help keep the adverse impact on the environment to a lower level. The concept of "living with floods", rather than fighting them, is the most effective way of preserving ecosystems.

5.7 In brief …

In order to mitigate adverse environmental impacts caused by structural measures of flood management and thus maintain river ecosystem health, the following issues need to be addressed:

- Many of the flood management measures have the potential to cause consequential hydrological, morphological and environmental impacts, with further significant impacts on socio-economic development.
- Non-structural flood management measures such as land use regulations; flood forecasting and warning; and disaster prevention, preparedness and response mechanisms; have limited environmental consequences and should be actively considered as viable options, both as independent or complementary measures.
- Dams are mainly built to meet the water demands of various economic activities such as hydropower, irrigation and drinking water. Flood management functions of dams are generally secondary in nature.
- While allocating water for various uses, the need to maintain "environmental flows" should be addressed. Design and operation of the existing and proposed dams should be suitably adjusted to keep the environmental impacts to a minimum.

- The ecological health of a river corridor depends not just on the water quality, or on the percentage of the total flows released, but also on the naturally variable quantity and timing of flows throughout the year.
- Reservoir operations with managed flood releases can help maintain near-pristine ecological conditions. Similarly, environmentally sensitive operation of bypass channels and detention/retention basins can help maintain the ecological health of riverine ecosystems.
- While designing embankments, the effects of lateral disconnection should be kept to a minimum by properly spacing the embankments and adequately assessing and balancing the economic and environmental consequences. Removal and setting back of embankments, where feasible, should be undertaken after a comprehensive study.
- Channelization should be avoided as far as possible as an option for flood mitigation. However, if adopted, use of soil bioengineering and soft revetments should be considered, so that flood management objectives are not compromised while mitigating impacts on the environment.

Table 3. Impacts of structural measures on various river corridor processes and possible mitigation measures

		Impacts on the environment	Possible mitigation measures
Dams and reservoirs	**Flow regime**	• Reduced seasonal variability of flow, i.e. low flows increased and high flow decreased • Increased flow fluctuations at hourly and daily timescales • Change in frequency and timing of floods (impacts depend on reservoir capacity and dam design and operation)	• Managed flow releases by reservoir operation, leading to seasonal variability of flow • Multiple and/or depth-selective intake structures for maintaining the natural seasonal temperature regime of released flows in reaches below dams, as well as water quality • Allowing for fish passage over weirs and dams, in both directions • Appropriate sediment bypassing devices • Bypassing large woody debris
	Sediment/ channel structure	• All sediment but the wash load fraction is trapped in the reservoir • Reduced sediment downstream leads to possible accelerated bed degradation and bank erosion in the reach immediately downstream of a dam • Possible changes in bed material composition and channel pattern downstream of the dam (e.g. from braided to single-thread) • Encroachment by riparian vegetation, decreasing the channel's conveyance capacity • Possible coastal erosion	
	Water quality	• Constantly cold water released from deep layers of the reservoir reduces the temperature variability of downstream river water • Possible accelerated eutrophication, due to the reservoir incorporating and trapping nutrients • Deeply plunging spillway releases can cause bubble-disease in fish because of nitrogen dissolution in water. • Water turbidity is decreased, which can lead to increased primary productivity • Reservoir will export plankton downstream, changing availability of food resources (most impacts on quality depend on a reservoir's retention time)	
	Habitat/ biodiversity/ natural resources	• River species largely replaced by lake species in reservoir • Native river species reliant on natural flow regime will disappear downstream of the dam • Changes in thermal regime affects many species, e.g. invertebrates • Short-term flow fluctuations (de-watering) result in stranding of organisms, in case of a hydropower dam • Most silt and organic matter is retained in reservoir, instead of fertilizing flood plains. This also has ecological effects in the fluvial, estuarine and coastal ecosystems • Floodplain structure and functioning is changed, as flooding is reduced or eliminated. This displaces some riparian trees and animals • Dams sever the longitudinal connectivity of the river which impedes or hinders the passage of fish and invertebrates along the river course, and also of some terrestrial animals along the river corridor • Exotic species can displace the locally adapted natives due to dam operations reducing extreme flows (both low and high), and/or extreme environ-mental conditions (e.g. high turbidity)	
Detention/retention basins	**Flow regime**	• Little impacts on natural flow regime, if the basin is designed only for storing flood water to reduce flood peaks downstream • Reducing temporally peak flood flows	• Artificial wetlands or permanent ponds can help in creating new habitat for many aquatic and terrestrial species, if the mitigation measures satisfy flood management objective • Detention basins should be designed, so as not to affect the flow and sediment regimes in the main channel
	Sediment/ channel structure		
	Water quality	• Increased temperature, decreased dissolved oxygen and eutrophication, etc., if water is stored during low flow season or in permanently wet basins • Little impacts on river water quality if the basin is used only during flooding	
	Habitat/ biodiversity/ natural resources	• The basin can help in creating habitats for many aquatic species (plants, fish, invertebrates, etc.), by serving as an artificial wetland • Little impact on river biodiversity if the basin is used only during flooding	

		Impacts on the environment	Possible mitigation measures
Table 3 *(continued)*			
Bypass/diversion channels	**Flow regime**	• Little impact if the bypass channel is used only during flooding for bypassing • Reduced river flow, stage and velocity in the bypassed reach if the water diverts flows permanently into the bypass channel • Increased flooding downstream, as waters are rushed through the bypass channel, leading to faster travel times	• Managed flow by design or operation to attain a new dynamic equilibrium under the altered flow and sediment regimes • A bypass channel can be planned in conjunction with a detention basin downstream of the bypass channel, in case the altered flow largely increases flooding downstream
	Sediment/ channel structure	• Possible aggradation in the bypassed reach, if the bypass takes only flood water but does not allow for intake of its share of bed load into the bypass channel	
	Water quality	• Little impact on river water quality in the original channel	
	Habitat/ biodiversity/ natural resources	• Little impact on biodiversity in the main channel	
Embankments	**Flow regime**	• Higher water stages and velocities at above bank full flows • Flood peaks increased downstream	• Embankments should be planned in conjunction with other structural measures such as dams and detention basins, as well as non-structural measures • Spacing of embankments should allow for the morphological lateral movement of the river • Embankment designs should minimize the disruption in lateral connectivity by setting balanced standards of protection based on economic and environmental criteria • Setting embankments farther back from river channel depending on land use conditions • Removal of embankments separating flood plain from river in combination with land use planning, if the flood plains are not occupied by human development
	Sediment/ channel structure	• Loss of connectivity between river and flood plain • Loss of pool and riffle patterns and other hetero-geneities in channel form • Increased erosion possible (both local scour and overall degradation) • Possible sedimentation downstream, of material eroded in embanked reach	
	Water quality	• Loss of exchange of nutrients and carbon with flood plain	
	Habitat/ biodiversity/ natural resources	• Loss of floodplain refuges and spawning areas for river species • Loss of floodplain forests (timber, fruits, medicines) • All floodplain structures, processes and species needing frequent inundation are affected • No more silt deposition on flood plain • No more habitat creation on the flood plain	
Channelization	**Flow regime**	• Increased channel slope, flow velocity, lower stages, reduced residence time, leading to increased flooding downstream (faster travel times and lower peak attenuation)	• Use of natural and permeable materials, i.e. soft revetments, instead of concrete revetments • Maintaining or re-introducing coarse woody debris as far as possible
	Sediment/ channel structure	• River bank and bed erosion (scour and degradation) • Sedimentation problems downstream • Total loss of heterogeneity in channel form	
	Water quality	• Reduction in nutrient and pollution assimilation capacity of river channel • In smaller (narrower) streams, increased temperatures • Increase in fine sediment load	
	Habitat/ biodiversity/ natural resources	• Loss of river habitat diversity, backwaters and refuges; loss of native river species • Loss of in-stream and riparian vegetation • Loss of organic material input • Lowering of floodplain water tables, affecting riparian vegetation and floodplain wetlands	

6. FACTORING ENVIRONMENTAL CONSIDERATIONS IN DECISION-MAKING PROCESSES

The goal of IFM is to maximize the net benefits from flood plains, to reduce flood risks, and to minimize loss of human life due to flooding in a sustainable manner. The need for a paradigm shift in thinking from flood control to flood management is the catalyst behind the concepts of IFM. It integrates land and water resources management in the river basin. Integrated Flood Management adopts a threefold approach of i) avoiding; ii) reducing; and iii) mitigating adverse environmental impacts without compromising on flood management objectives. It is desirable to minimize the negative impacts of flood management interventions that limit natural productivity, ecosystem health and services provided by the ecosystem, including flood alleviation processes to a reasonably practical level. This chapter provides a framework for factoring environmental considerations into the decision-making processes at various levels: policy formulation, basin planning, project design and implementation and operation.

6.1 Decision-making processes

Flood alleviation benefits are essentially for the public good, and thus, flood management has to be carried out through a public policy framework. The multi-dimensional nature of flood management options necessitates an inclusive and participatory approach to the decision-making process: starting from public policy through to basin planning and project implementation. There are various constraints in any decision-making process in flood management, which can be broadly categorized into: physical, financial, social, political, legal and environmental. Physical and financial considerations have largely been tackled through economic analysis with little or no attention to social and environmental concerns. These issues, in any policy making are related to societal values, either regarding the perceptions of risks or the trade-offs between development and environmental preservation. In order to minimize the role of subjective factors there is a need for an environmentally sensitive framework to be established within decision-making processes (Figure 10).

A number of public policies, not directly linked to flood management, also influence flood risks, (e.g. land policies) and therefore, form an important input to the process of flood management policy formulation. These related public policies have to be factored into the integrated flood management policy formulation through a strategic and collaborative planning framework. Such a framework should involve stakeholders within as well as outside government circles.

Catchment characteristics undergo continuous change due to human activities, influenced by land policies, which can change the magnitude of floods. Urbanization in upper catchments promotes higher runoff downstream, thereby increasing the flood hazard, particularly in smaller catchments. These factors, along with the flood risks and social perceptions towards them, determine the goals of flood management in a given basin. Integrated water resources management plans provide a basic framework for developing a basin flood management plan. How much risk a society is ready to take, in order to achieve its developmental objectives of poverty alleviation and/or sustainable development, guides various options. It is important to analyse the risks of living in or using a flood plain, based on both the negative and positive impacts of floods[65] under a given situation. All related agencies, led by the flood management agency,

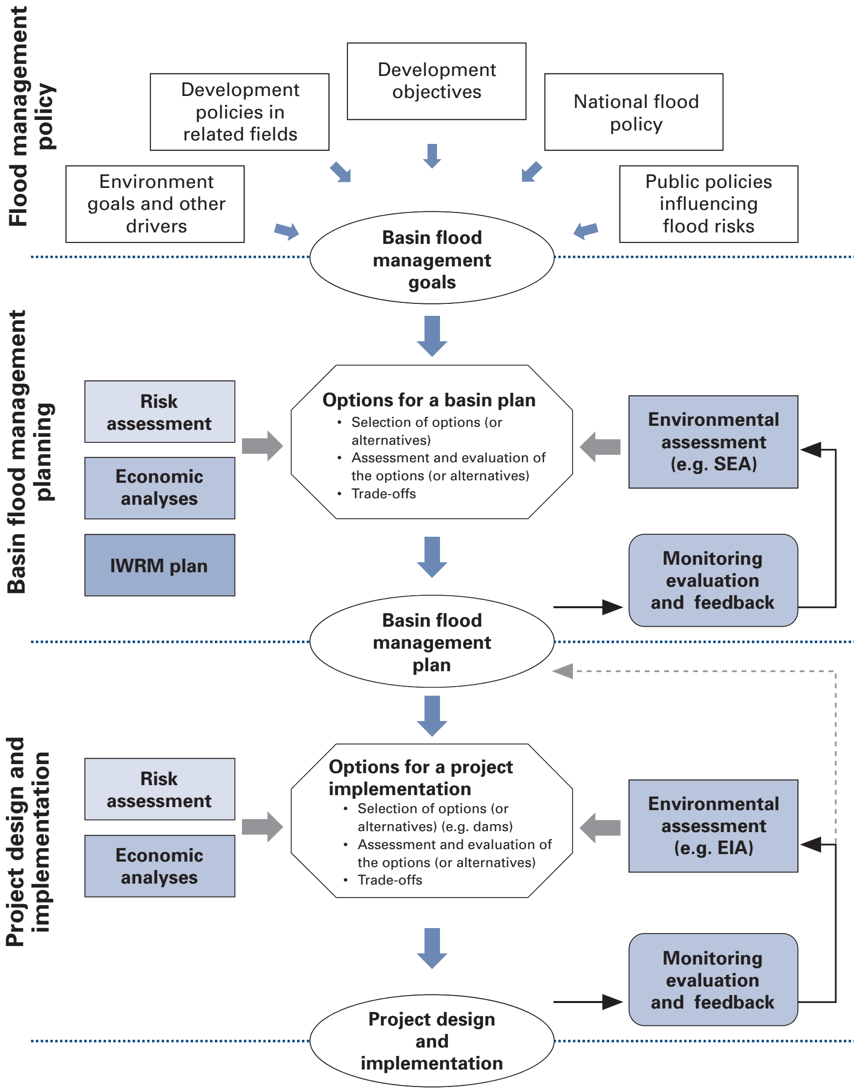

Figure 10. Environmentally sensitive flood management decision-making framework

should participate in this process and view flood management from a perspective that transcends flood management agency/department.[66] The environmental assessment at a strategic level, accompanied with monitoring, needs to be incorporated within the planning framework. Feedback on the effectiveness of basin planning in achieving the desired basin flood management goals is important.

Various flood management options should be drawn up on the basis of the basin plan and assessed through a participatory process using various economic analysis tools. Such economic analysis should incorporate valuation of ecosystem services. An environmental impact assessment of various options, design alternatives and operation principles should be carried out, in order to find ways and means to mitigate the adverse environmental impacts to a minimum. A monitoring mechanism should be put in place to carry out a baseline survey of the existing health of the ecosystems, with the provision of regular evaluation and mid-course correction, embracing an adaptive management approach.

In order to factor environmental considerations in such decision-making processes, there is need for an overall framework with the following elements:

- Scientific understanding and analysis;
- Environmental assessment;
- Environmentally sensitive economic analysis;
- Stakeholder involvement;
- Adaptive management approach;
- Monitoring; and
- Enabling mechanism.

6.2 Scientific understanding and analysis

Integrated Flood Management calls for a multidisciplinary approach to flood management, involving various stakeholders. It promotes a dialogue among professionals from various disciplines, coming from different paradigms, to explore, among others, shared perceptions and common goals. These disciplines include practitioners and researchers from various fields: ranging from public administration, agriculture, sociology, ecology, hydrology/hydraulics, morphology, river engineering, etc. Such a multidisciplinary approach must be based on accessible information, a common language for the debate and a transparent decision-making process.

Scientific knowledge of basic concepts concerning the morphology and ecology of rivers and their flood plains, and how these are driven by the flow regime, is fundamental to understanding the ecosystem processes in a river basin and the impacts of flood management measures on those ecosystems. Environmentally sensitive design, execution and operation of new projects; and mitigation of adverse impacts of existing works through better operation and restoration can be undertaken, only if such scientific concepts are well understood.

There is an urgent need to develop intensive cooperative investigation between ecologists, hydrologists and river and water resources engineers on interactions of the hydrological cycle with human activities, land surface characteristics and ecosystems. Eco-hydrology/eco-hydraulics analyses the dynamics of the structural and functional characteristics of ecosystems to develop practical procedures to include ecosystem conservation and/or restoration in a multi-criteria approach for managing various water and catchment uses. Research activities and technologies within this discipline, applied to the specific needs of flood management, need to be shared with and translated into readily understandable language for other disciplines. Institutions dealing with flood mitigation should direct their efforts towards better understanding of the consequences of anthropogenic and natural change in the basin in relation to flood hazards and the impact of mitigation measures on the environment.

6.3 Environmental assessment

Environmental assessment is a tool for intensive examination, necessary for decisions that have a diverse and significant environmental impact.[67] Environmental assessment is applied at various levels of decision-making. Environmental Impact Assessment (EIA) is applied at project design and implementation levels, while Strategic Environmental Assessment (SEA) is used at policy, plan and programme levels.

Environmental assessment at a strategic level

In order to factor environmental concerns into management decisions, it is important to start at the strategic level.[68] Strategic Environmental Assessment can be described as a participatory approach for upstreaming environmental and social issues in order to influence processes for development planning, decision-making and implementation at the strategic level.[69] The SEA processes are given in Box 5.

In how much detail a development plan should be assessed, within the framework of SEA, is dependent on the planning objectives. If the scope of the planning is too broad to assess the environmental impact, a general qualitative description of foreseeable cause-effect scenarios is sufficient. In most cases, qualitative information on the basis of expert judgment should be sufficient at the strategic level. Quantitative assessment may be required where environmentally

Box 5. Strategic Environmental Assessment processes

Strategic Environment Assessment involves various steps: screening; scoping; identification, prediction and evaluation of impacts; mitigation; and monitoring. These are briefly discussed below.

Screening: This activity is conducted to answer the following threshold question. For any particular policy, plan or programme, should an SEA be conducted? If the proposal has an environmental impact, then one moves to the next step.

Scoping: Given the determination that an SEA must be conducted, what are the impacts that the SEA must assess? In other words, what is the scope of work (or "terms of reference") for the SEA? Typically, the scope of work of an SEA is determined by professional experts using their collective judgment, and in some jurisdictions the public is invited to participate in scoping.

Identification, prediction and evaluation of impacts: The process of forecasting and evaluating impacts in SEA can employ some of the same tools and procedures used in project-level EIA. As in the case of EIA work, professional judgment often plays a major role. In contrast to EIA work, however, the need to trace indirect (or secondary) environmental effects can be expected to play a more dominant role in SEAs. This is because many policies, plans and programmes subject to SEA are written to produce changes in economic and social effects, which can, in turn, produce significant indirect (and sometimes inadvertent) environmental effects. These interactions between economic, social and environmental effects play a key role in "integrated assessments."

Mitigation: Mitigation measures are intended to avoid, reduce or offset the adverse effects of an action, such as the decision to approve a policy or implement a plan.

Monitoring: Programmes to monitor the effects of a policy are often advocated because such monitoring can alert responsible authorities to the unintended outcomes that may be controlled using mitigation measures. Also, by comparing predicted outcomes with those observed via monitoring, analysts may be able to improve their ability to predict impacts in the future.

Source: World Bank, 2005. *Integrating Environmental Considerations in Policy Formulation: Lessons from Policy-Based SEA Experience*, Environmental Department, World Bank, Washington, DC.

negative impacts have already reached a threshold, or where cumulative impacts are expected. Such an assessment should be documented with clear evidence, including details of the kind of analyses carried out; the data used for the analyses; and the assumptions and hypotheses adopted.

For effective SEA, it is important to facilitate a dialogue between environmental and development authorities as well as with informed public representatives. Information exchange and use, with readily understandable data, facilitate communication among the various stakeholders and experts, play a vital role in ensuring close collaboration and help keep the decision-making process transparent.

Strategic Environmental Assessment has, however, no single accepted approach that can be applied to all cases because of differences in scope, comprehensiveness, duration and context at various levels – national and regional, policy and planning, developing and developed countries, etc. Political will is also important in carrying out SEA.[70] Socio-political pressures may persuade unwilling development agencies to implement SEA. At the same time, a legislative requirement may be effective in developing the political will to carry out SEA as a long-term strategy. Some formal provision for SEA, for example, can be made under EIA or other legislation (e.g. the Netherlands[71]), or as a separately administrated but related procedure (e.g. Canada,[72] Denmark[73]), while some others are carried out through a comparable, less formalized process of policy and plan appraisal (e.g. UK[74]).

Environmental assessment at a project design and implementation level

Environmental Impact Assessment is used to identify the environmental and social impacts of the proposed project prior to decision-making in order to predict environmental impacts at an early stage in project planning and design; find ways and means to reduce adverse impacts; shape projects to suit the local environment; and present the predictions and options to decision makers. The key elements of an EIA are: identification of issues and concerns of interested parties (scoping); evaluation of the importance of these issues to assess the need for EIA (screening); identification of possible options; exploring mitigating measures that deal with uncertainty; review of actions proposed to prevent or minimize the potential adverse effects of the project; and issuing environmental statements to report the findings of the EIA.[75]

The environmental impact statement usually requires a description of the proposed activity, a consideration of reasonable alternatives (as well as the consequences of the no-action alternative) and a description of the environment likely to be significantly affected by the proposed activity and its alternatives. Thereafter, the potential environmental impacts must be described and assessed in terms of their significance; mitigation measures for reducing adverse environmental impacts must be proposed; and the underlying assumptions, methodologies and data used in the assessment must be made explicit.

Environmental Impact Assessment has been made mandatory by law in many countries. The size and the geographical setting of the proposed project are important in determining its environmental significance. It is also important to notify and consult with the other countries where the project may have a significant adverse environmental impact across a national boundary.

Consultation and public participation is the key to carrying out both EIA and SEA. While decision-making authority is retained by governments, interaction with people and eliciting feedback allows affected populations to influence the decision-making process by raising issues that should be considered in scoping, project design, mitigation, monitoring and management plans and analysis of the alternatives.

6.4 Environmentally sensitive economic analyses

Cost-benefit analysis (CBA) and multi-criteria analysis (MCA) are methodologies that support decision-making when a suite of options has to be analysed in relation to their economic aspects.[76] cost-benefit analysis is useful in enabling the assessment of various options, by comparing their costs versus their benefits in monetary terms. Now that the economic value of many of the ecosystem services can be assessed, the cost of losing ecosystem services through adverse environmental impacts can also be factored into the CBA of a particular option. Different valuation methodologies are now available and the choice depends on whether one is considering the direct values or the indirect values[77]. However, where economic values of environmental and societal aspects are not amenable to assessment or are difficult to assess, a CBA may mask the true costs and benefits of a project, particularly the costs associated with the loss of ecosystem services.

Multi-criteria analysis is a complementary approach to CBA. It involves judging the expected performance of each development option against a number of criteria or objectives. These techniques can deal with complex situations, involving uncertainty as well as the preferences of many stakeholders. This is particularly highlighted, when the problem presents conflicting objectives and when these objectives cannot be easily expressed in monetary terms. As such, weights are assigned to different objectives and criteria based on their perceived societal importance into a multi-criteria model. These weights have an important role in the MCA techniques and should be chosen in a transparent manner, to demonstrate their influence on final outcomes. A weighted average can provide the overall indicator of performance for each option. Multi-criteria analysis can be useful in ranking options, short-listing a limited number of options for subsequent detailed appraisal (say through CBA), or simply separating acceptable from unacceptable options. The decision is easy when one of the options emerges as dominant with respect to all of the criteria. But, in most cases, some options will be better against one criterion but worse against another. The usefulness of MCA is clear in such situations.

The question of trade-off occupies a central place in such situations. Weighting or ranking becomes necessary to deal with such cases and requires the appropriate involvement of stakeholders at various stages of analysis. There are two different ways in which these weights can be assigned. In the first, several experts (from a variety of research fields) are called upon to propose weights based on technical judgments. Weights determined by experts, however, cannot be regarded as free from subjective biases as compared with ones determined by the concerned public. In the second, various stakeholders, such as community groups, NGOs and others, are involved in assigning weights in a participatory process. For a meaningful participation of stakeholders, economic analysis should also show how the costs and benefits of various options, including those due to changes in the ecosystem, are distributed, i.e., who benefits and who bears the cost.

Despite its shortcomings[78], MCA is better than the informal or intuitive judgments often made by decision makers, as it provides an analytical base for decision-making. It is transparent and based on structured and explicit elements of knowledge. Multi-criteria analysis provides a framework for stakeholders to explore the nature of the choices, to determine which are the critical factors, to discover their own preferences, and to simplify the process of selecting the critical options. Since economic evaluation involves societal values, it is appropriate to carry out CBA/MCA in conjunction with and in close consultation with and participation of the public affected by the project.

6.5 Stakeholder involvement

Genuine stakeholder involvement[79] is at the core of decision-making processes. The main purpose of stakeholder involvement is to ensure implementation of IFM principles where stakeholders participate in identifying, shaping, developing, logically validating and implementing the plans and projects, as well as in monitoring and evaluating their impacts. As an integrated approach to flood management requires a combination of water resources, land use, environmental, and flood management strategies, it calls for coordination between different sectoral planning processes at various levels of decision-making.

Stakeholder involvement at various stages of decision-making varies considerably in accordance with existing legal and policy regimes. Some decisions are vested completely in government officials, others rest on government with some space for communities to intervene, while still others could be implemented effectively only with active community participation.

In general, the public has less interest to participate in basin policy issues, since they find the flood issues at basin level more abstract. It may also not appear to be of immediate concern as these consultations are sometimes time-consuming and require long-term engagement. Even though public interest tends to be relatively lower at the strategic level than that at the project design and implementation level, public involvement in the decision-making process is important. Therefore, representatives of stakeholders, regional authorities, community groups, NGOs, etc., need to be involved rather than general public at the policy and basin planning level. This involvement is guided by the condition, level and characteristics of the policy and plan. A useful tool in this regard is role playing.

On the other hand, at project design or implementation level, where the project directly affects local people, communities have more interest to get involved in the decision-making processes. Public, competent authorities and other ministries, local governments, NGOs, politicians, etc., need to be involved to make the process of decision-making more transparent and legitimate.

For a successful participatory planning, it is important to develop enabling participatory mechanisms through an appropriate legal and institutional framework and capacity-building of the various stakeholders.

6.6 Adaptive management approach

Scientific knowledge about the existing conditions of ecosystems is fragmentary and the impact of human interventions on them is not fully understood. In order to account for this lack of scientific certainty, precautionary principles have been recommended in international agreements. In the context of environmental protection, principle 15 of the Rio Declaration on Environment and Development[80] provides that:

> "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

A similar precautionary approach is also recommended by the United Nations Framework Convention on Climate Change[81] with respect to factoring climate change issues.

Adaptive management has been widely recognized as the appropriate approach to deal with such scientific uncertainties, wherein, decisions are made as part of an ongoing science-based process. It involves planning, acting, monitoring and evaluating applied strategies, and incorporating new knowledge as it becomes available into management approaches (see Figure 11). Monitoring and evaluation results are used to modify management policies, strategies and practices.[82] It is a departure from traditional management, and views management actions as learning experiments. Adaptive management explicitly defines the expected outcomes, design methods to

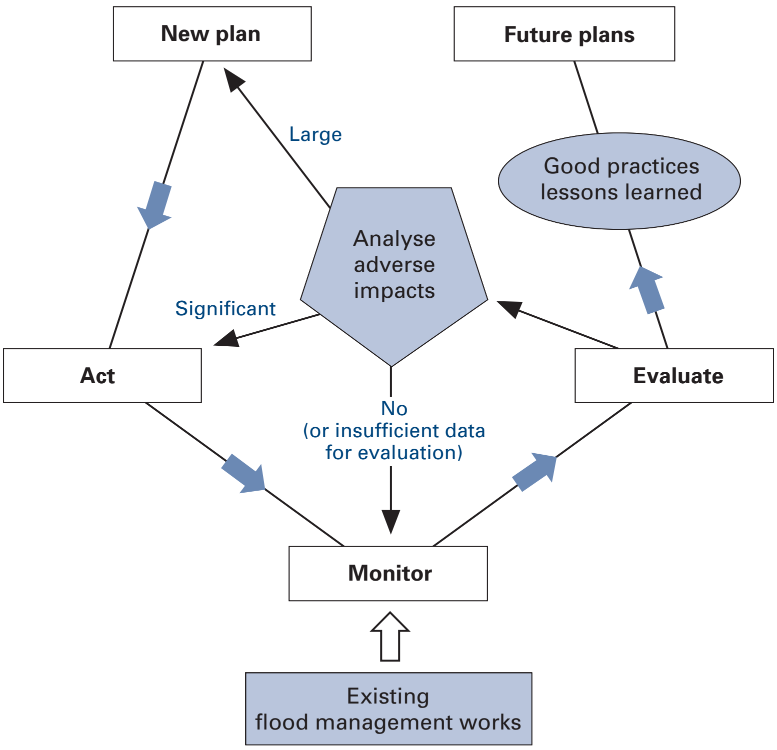

Figure 11. Adaptive management approaches

measure responses, collects and analyses information to compare expectations with actual outcomes, learns from the comparisons, and changes actions and plans accordingly.[83] Therefore, adjusting management direction requires a willingness to experiment and accept occasional failures.[84]

Adaptive management starts right at the stage of drawing up a plan. It encompasses both deliberate experimentation to gain new knowledge, known as active adaptive management, as well as the ongoing process of using monitoring and inventory information to assess the effects of management actions on ecosystem health, known as passive adaptive management. Active adaptive management involves constructing a range of alternative response models (hypotheses) based on the existing data, calculating the long-term benefits, and then weighing them against costs. It is also important to develop an exit strategy to deal with unexpected or undesirable outcomes of certain scientific research.[85] On the other hand, passive adaptive management is treated as the management option, assuming that the model on which the predictions are based is correct.[86] The monitoring of the results forms a crucial input and is used to evaluate the impacts, particularly the adverse impacts. If these impacts are significant, it may require a review of the action taken, such as operational procedures or project design parameters. On the other hand, if these impacts are large, the plan is reviewed with possible implications on the policies. Evaluation of both active as well as passive adaptive management components forms a sound basis for the knowledge base that can help in better understanding of the processes and developing future plans.

If structural flood management works are already in place and have apparent adverse impacts, it is not always realistic to remove them. In such situations, the existing systems and their performance need to be appropriately assessed in a transparent manner. Adaptive management can play an important role in such a situation by starting with monitoring the current conditions or evaluating existing data (if available). If progressive environmental degradation is established or is foreseen, basin plans may require a review.

6.7 Monitoring

Adaptive management requires continuous monitoring of the state of the environmental health and its evaluation at regular intervals. The monitoring must be statistically sound and scientifically credible, particularly for effectiveness and validation.

The importance of monitoring has been recognized from various perspectives. Pre-plan monitoring of various natural processes provides the basic input for assessment of resources, risks and development options. Monitoring at a development planning level is focused on actions taken based on the selected plan and factors of environmental impacts indicated in environmental assessment at the strategic level. The items to be monitored can be whether: the objectives of the plan are achieved, the actions are taken appropriately based on the plan, and the plan needs to be re-established or modified. However, it should be noted that time and continuous effort are required to assess the plan. Evaluation of a strategic plan is sometimes difficult, since the objectives of the plan might be realized only after several years. Also, certain external factors, which are not accounted for in the SEA, may influence environmental impacts much more than the impacts of action taken under the plan.

During- and post-implementation monitoring is important at the project level, in order to assess whether the flood management measure has in fact succeeded in meeting the desired objectives. Monitoring of the state of the environment enables to assess whether the extent of the impacts foreseen by environmental assessment at the project design and implementation level is being manifested and whether the measures taken to prevent them are effective and to what extent. Lessons learned through monitoring and evaluation can improve the methodology applied in future project designs.

Monitoring environmental impacts can be achieved through indicators designed according to the environmental objectives. Various aspects of the environment such as changes in land use, habitat diversity, the distribution of wetlands and indicators of the state of fisheries, should be included in the monitoring. Monitoring should be designed to address both the direct effects on the state of the environment, such as the volume of emissions or the use of natural resources, and indirect effects that can be monitored by examining trends in production, consumption, etc.

6.8 Enabling mechanism

Most countries lack the organizations capable of adopting integrated approaches and investment that supports effective organizational learning and cross-organizational interactions. The communication gap among various professional streams and between experts and the public at large further complicates the process of putting such a framework into practice. There is need for capacity-building at various levels and institutions that can support such a framework aided by legal mechanisms.

Exchange of information across spatial and temporal scales is fundamental in improving the unsatisfactory state of our knowledge at all levels. To adopt environmentally friendly flood management, there is a need for organizations that can enforce shared responsibilities for generating and communicating knowledge for continuous learning. This also requires a behavioural change at various levels. It is, therefore, essential to create a harmonized network of communication between the different institutions and organizations involved as well as with the community at large. Monitoring the state of the environment forms an essential part of such a learning process.

While it is only one of a number of influences on flood management, appropriate legal and institutional provisions play a vital role in the achievement of the objectives of IFM.[87] In order to implement flood management plans within the context of IWRM and support adaptive management approaches, the way institutions work has to be reformed. There is a need for greater transparency and sharing responsibility but at the same time providing for innovations and learning through genuine experimentation. Coordination among government departments, research institutions and universities needs to be improved. Promoting successful multiple stakeholder involvement, entails the development of technologies and institutions that fit into the natural, cultural and social backgrounds of the region.

The role of a legal regime in land and water use management is critical to the success of IFM, and can influence the behaviour of many agencies that might not otherwise be directly involved in implementing flood management plans. From an environmental perspective, law can protect and entrench the rights and interests of the environment that might otherwise have no influence over decision-making. Water related ecosystems should be considered as legitimate water users. Various environmental assessment processes such as SEA and EIA, along with details of the relevant procedures that must be followed in obtaining planning permissions for projects and programmes, with a likely significant effect on the environment, should be implemented through a legal framework. This also includes rights of public access to environmental information and the role of respective stakeholders to participate in decision-making.

While coordinated land and water management at the basin scale is difficult in the absence of an adequate institutional framework, it becomes further complicated in the case of transboundary basins where the number of actors increases drastically and many disparities exist in ideologies, ethics, legislation, governance, data acquisition and quality systems, engineering codes and practices. In the transboundary arena, the concern for the natural environment is embodied in a number of international conventions, including but not limited to the Ramsar Convention on Wetlands; the Basel Convention, which regulates the transboundary movements of hazardous waste; and the Aarhus Convention dealing with access to environmental information.[88] Further and more specific environmental agreements exist on a basin-wide or bilateral basis. Bi- and Multilateral Environmental Agreements can also provide political momentum for incorporating desired environmental provisions within national legal frameworks.

6.9 In brief …

In order to translate environmental considerations appropriately into decision-making processes in flood management at policy, planning and project design and implementation level, together with other relevant aspects such as legal and institutional, social and economic aspects, including stakeholder involvement, the following should be addressed:

- From the environmental perspective of IFM, a threefold approach of avoiding, reducing and mitigating the adverse environmental impacts without compromising flood management objectives, is recommended.
- Scientific knowledge of basic concepts concerning the morphology and ecology of rivers and their flood plains, and how these are driven by the flow regime, is fundamental to understanding the ecosystem processes in a river basin and the impacts of flood management measures on the environment.
- A number of public policies not directly linked to flood management also impact flood risks. In order to factor environmental considerations in decision-making processes within IFM approaches, there is a need for an overall framework with the following elements:
  - Scientific understanding and analysis;
  - Environmental assessment;
  - Environmentally sensitive economic analysis;
  - Stakeholder involvement;
  - Adaptive management approach;
  - Monitoring; and
  - Enabling mechanism.
- Environmental assessment at various levels of decision-making is important. Strategic Environmental Assessment (SEA) is a proactive approach at the strategic level. It can help

pre-identify key issues that should be addressed in the subsequent Environmental Impact Assessment (EIA), which are implemented at the project design and implementation level. Strategic Environmental Assessment supports EIA in screening, scoping and thereby integrating environmental considerations into decision-making processes.

- Cost-benefit analysis (CBA) and multi-criteria analysis (MCA) are useful methodologies that support decision-making when a suite of options has to be analysed in relation to their economic aspects. Valuation of the services provided by the ecosystems should essentially be included in these analyses.
- Stakeholder involvement is crucial for SEA/EIA and CBA/MCA where one can achieve acceptable trade-offs. There is the need for an enabling mechanism for effective stakeholder involvement. Multi-criteria analysis can be used as a framework for stakeholders to explore the nature of the choices, to determine which are the critical factors and to discover their preferences.
- In order to deal with scientific uncertainly, adaptive management approaches should be embraced in order to make mid-course correction. Monitoring of the effectiveness of an adopted plan and project is important to make any mid-stream modifications in planning and implementation.
- All relevant aspects of the environment such as changes in land use, habitat diversity, the distribution of wetlands, indicators of the state of fisheries and the species sensitivity and diversity of macro-invertebrate communities, should be included in the monitoring accordingly.
- The role of a legal regime can influence the behaviour of many agencies that might not otherwise be directly involved in implementing flood management plans. Law can protect and entrench the rights and interests of the environment that might otherwise have no influence over decision-making.

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TERMINOLOGY

Active adaptive management: a deliberate experiment for the purpose of learning. It involves constructing a range of alternative response models (hypotheses) based on existing data, calculating the long-term value of the management, and then weighing this long-term value against any short-term costs incurred in finding out which is correct.

Adaptive management: a way of establishing hypotheses early in the planning, then treating the restoration process as an experiment to test the hypotheses.

Aggradation: process of raising a land surface by the deposition of sediment.

Alluvial: of, pertaining to or consisting of alluvium deposited from flowing water or belonging to such a deposit.

Aquifer: permeable water-bearing formation capable of yielding exploitable quantities of water.

Beach forests: forests found above the high-tide mark on sandy soil.

Biological diversity/Biodiversity: the variety and variability among living organisms and the ecological complexes in which they occur. It encompasses different ecosystems, species, genes and their relative abundances.

Bypass channels: channel built to divert flows from a point upstream of a region to a point downstream.

Catchment: the area from which rainfall flows into a river, reservoir, etc.

Channelization: a process of channelling or carving a route in order to increase the flow depths for navigation or/and reduce flood peaks by increasing the overall conveyance capacity through reducing friction and confining the flows into one single channel.

Coastal ecosystems: inland forests and woodlands that extend to the sea. They are determined by input of fresh water into the system – quantity, quality and timing – and the daily and seasonal influences of tides causing changes in salinity, temperature, turbidity and energy flux. Such communities include mangroves, beach forests and peat forests.

Connectivity: a measure of how spatially continuous a river corridor or a matrix is. Longitudinal connectivity: upstream catchment and downstream corridor reaches. Lateral connectivity: the river and its flood plain. Vertical connectivity: surface with subsurface river corridor and hyporheic zones.

Cost-benefit analysis (CBA): a technique to compare the various costs associated with an investment with the benefits that it proposes to return. Both tangible and intangible factors should be addressed and accounted for.

Cyclonic storms: storm caused by the activity of an atmospheric depression.

Dam: structure constructed across a valley for impounding water or creating a reservoir.

Degradation: disintegration and wearing down of the surface of rocks, cliffs, strata, streambeds, etc., by atmospheric, aqueous, biological and other actions.

Detention and retention basins: basins for the storage of flood waters, of varying design. Detention refers to the holding of runoff for short periods to reduce peak flow rates, later releasing it into watercourses. A detention basin typically has a downstream outlet into the main river channel. Retention refers to schemes in which storm water runoff or flood water over-spills are held for considerable periods, causing water to continue in the hydrological cycle via infiltration, percolation and evapo-transpiration, and not via direct discharge to watercourses.

Dissolved oxygen (DO): the amount of free (not chemically combined) oxygen dissolved in water, wastewater or other liquid. Adequate concentrations of dissolved oxygen are necessary for the life of fish and other aquatic organisms and the prevention of offensive odours.

Eco-hydrology/eco-hydraulics: the science of study of ecosystems and their interaction with hydrology/hydraulics.

Ecological integrity: ecological integrity refers to the capacity to support and maintain a balanced, integrated, adaptive ecosystem, having the full range of elements (genes, species, assemblages) and processes expected in the natural habitat of a region.

Ecology: the study of the relationships between plants and animals (including humans) and their environment.

Ecosystem: a dynamic complex of plant, animal and microorganism communities and their non-living environment, interacting as a functional unit.

Ecosystem approach: a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way.

Ecosystem services: the benefits people obtain from ecosystems. These services are highly interlinked and include provisioning, regulating and cultural services. In addition there are the supporting services that are needed to maintain other services and can have relatively indirect and short-term impacts on people.

Embankments (also referred to as levees and dykes): water-retaining earthworks used to confine stream flow within a specified area along the stream or to prevent flooding due to waves or tides.

Environment: surroundings in which an entity operates. This includes air, water, land, natural resources, flora, fauna, humans and their interrelationships.

Environmental flow: an environmental flow is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated.

Environmental Impact Assessment (EIA): a tool used to identify the environmental and social impacts of a project prior to decision-making. It aims to predict environmental impacts at an early stage in project planning and design, find ways and means to reduce adverse impacts, shape projects to suit the local environment and present the predictions and options to decision makers.

Eutrophication: enrichment of water by nutrients, especially compounds of nitrogen and phosphorus, that will accelerate the growth of algae and higher forms of plant life.

Evaporation: Emission of water vapour from a free surface at a temperature below the boiling point.

Flood: (1) Rise, usually brief, in the water level in a stream to a peak from which the water level recedes at a slower rate. (2) Relatively high flow as measured by stage height or discharge. (3) Rising tide.

Flood control: protection of land areas from overflow, or minimization of damage caused by flooding.

Flood control dam: dam used to control floods by storing all or a portion of the flood waters in the reservoir particularly during peak floods and then releasing the water slowly over time.

Flooding: (1) Water overflowing the bankfull stage of a natural or artificial waterway. (2) Accumulation of water caused by surface runoff in low-lying areas not usually submerged.

Flood plain (n.)/floodplain (adj.): defined by hydrologists as the area flooded at a recurrence interval of once in 100 years (Bhowmik and Stall, 1979). Defined by geomorphologists as a largely horizontal alluvial landform adjacent to a river channel, separated from it by banks, constructed from sediment by the river in the present climate and flow regime, and overflowed during moderate flow events (Nanson and Croke, 1992; Leopold, 1994). Defined by ecologists as the areas that are periodically inundated (usually annually) by the lateral overflow of rivers or lakes, or by direct precipitation or groundwater; the resulting physico-chemical environment causes the biota to respond by morphological, anatomical, physiological, phenological, and/or ethological adaptations, and to produce characteristic community structures (Junk et al., 1989).

Flood pulse concept: the idea that the pulsing of river discharge, the flood pulse, is the major force controlling biota in river floodplain systems (Junk et al., 1989). Lateral exchange between the flood plain and river channel, and nutrient cycling within the flood plain, are postulated to have a more direct impact on biota than nutrients spiralling from upstream to downstream in the river channel; the bulk of the animal biomass in such a system is believed to be derived from production in the flood plain, not from downstream transport of organic matter produced elsewhere in the basin.

Flow regime: quantity, frequency and seasonal nature of water flows.

Forests: all vegetation formations with a minimum of 10 per cent crown cover of trees and/or bamboo with a minimum height of 5 m and generally associated with wild flora, fauna and natural soil conditions.

Geomorphology: the study of the arrangement and form of the earth's crust and of the relationship between these physical features and the geologic structures beneath.

Hydrology: (1) Science that deals with the waters above and below the land surfaces of the earth, their occurrence, circulation and distribution, both in time and space, their biological, chemical and physical properties, their reaction with their environment, including their relation to living beings. (2) Science that deals with the processes governing the depletion and replenishment of the water resources of the land areas of the earth, and studies the various phases of the hydrological cycle.

Infiltration: flow of water through the soil surface into a porous medium.

Integrated Coastal Zone Management (ICZM): a planning and coordination process which deals with development management and coastal resources and which is focused on the land/water interface.

Integrated Flood Management (IFM): a process promoting an integrated rather than fragmented approach to flood management, integrating land and water resources development in a river basin within the context of Integrated Water Resources Management, with the aim of maximizing the net benefits from flood plains while minimizing loss of life from flooding.

Integrated Water Resources Management (IWRM): a process promoting the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner, without compromising the sustainability of vital ecosystems.

Lakes and ponds: water bodies that are generally lentic.

Lentic: still water systems such as lakes and ponds.

Lotic: moving water systems such as streams and rivers.

Managed flood: a controlled release of water from a reservoir, inundating a specific area of downstream flood plain or river delta in order to restore and maintain ecological processes and natural resources for dependent livelihoods.

Mangroves: the most typical forest formations of sheltered coastlines in the tropics and subtropics. They consist of trees and bushes growing below the high water level of spring tides.

Meander: one curved portion of a sinuous or winding stream channel, consisting of two consecutive loops, one turning clockwise and the other anticlockwise.

Morphology: study of the structure, form or shape of meteorological phenomena, such as clouds or ice crystals; including the classification of these phenomena.

Multi-criteria analysis (MCA): a set of procedures of analysis of complex decision problems involving non commensurable, conflicting criteria on the basis of which alternative decisions are evaluated.

Nutrient: substance, element or compound necessary for the growth and development of plants and animals.

Outlet: opening through which water flows out or is extracted from a reservoir or stream.

Oxbow: abandoned part of a former meander, left when the stream cuts a new, shorter channel.

Passive adaptive management: the management option, assuming that the model on which the predictions are based is correct. Passive adaptive management requires monitoring and evaluation of project activities, as well as some aspects of management experiments.

Purification: treatment of water (or sewage) to change harmful or undesirable physical properties and remove harmful and undesirable chemical substances and living organisms.

Reservoir: body of water, either natural or man-made, used for storage, regulation and control of water resources.

Restoration: return of an ecosystem to a close approximation of its condition prior to disturbance.

River continuum concept (RCC): the idea that a continuous gradient of physical conditions exists from headwaters to mouths of rivers, and that structural and functional characteristics of biological communities are adapted to conform to the most probable position or mean state of the physical system (Vannote et al., 1980). Producer and consumer communities establish themselves in harmony with the dynamic physical conditions of a given reach, and downstream communities are fashioned to capitalize on the inefficiencies of upstream procession of organic matter. Both upstream inefficiency (leakage) and downstream adjustment seem predictable.

River corridor: includes both the flood plain and the river channels.

Riparian: in legal term, riparian means that the state whose territory touches a river flowing on the surface of the drainage basin, according to the ILA Helsinki Rule (ILA, 1966) (although riparian is a synonym with riverine as per Oxford Dictionary and as such used by certain disciplines).

Riverine: an area that includes the river channel and the adjacent land directly connected with the river.

Runoff: a mixture of water and soil along with any other organic or inorganic substances that may exist in the land; is the product of precipitation, snowmelt, over-irrigation, or other water coming in contact with the earth and carrying matter to streams, rivers, lakes and other surface water bodies.

Sediment: material transported by water from the place of origin to the place of deposition. In watercourses, sediment is the alluvial material carried in suspension or as bed load.

Sedimentation: process of settling and depositing by gravity of suspended matter in water.

Serial discontinuity concept: the idea that dams shift the physical and biological characteristics of streams and rivers away from the pattern predicted by the river continuum concept (Ward and Stanford, 1983). A dam may make conditions more like those of the headwaters (an upstream shift) or more like those downstream, or it may have a negligible effect. Multiple dams create multiple discontinuities in the expected or natural pattern of streams and rivers.

Sewage: water supply from a community after it has been fouled by various uses. It may be a combination of the liquid or water-carried domestic, municipal and industrial wastes, together with such groundwater, surface water and storm water as may be present.

Storm surges: elevation of sea or estuary level caused by the passage of a low pressure centre.

Strategic Environmental Assessment (SEA): a systematic process for evaluating the environmental consequences of proposed policy, plan or programme initiatives in order to ensure that they are fully included and appropriately addressed at the earliest possible stage of decision-making, on a par with economic and social considerations.

Tsunamis: great sea wave produced by an underwater earthquake, volcanic eruption or landslide.

Turnover/turnover rate: the process of local extinction (e.g. on islands) of some species and their replacement by other species. The turnover rate is the number of species eliminated and replaced per unit time (MacArthur and Wilson 1967: 191)

Water quality: physical, chemical, biological and organoleptic properties of water.

Wetlands: an area of marsh, fen, peatland. These can be natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or saline, including areas of marine water the depth of which at low tide does not exceed 6 m.

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