Title:	**Environmental Flow Requirements for Rivers** **An integrated approach for river and coastal zone management**

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Abstract

Environmental flow requirements (EFR's) are being assessed for an increasing number of rivers world-wide. Numerous methods are used, ranging from simple hydrological indices to complex, holistic procedures in which not only the ecological water needs are assessed, but where also the local demands of human communities along the river are taken into account. This report provides an integrated approach to the assessment of environmental flows. It reviews the existing methods and concludes that the vast majority of these methods tend to narrowly focus on the instream ecological features of riverine systems. Currently, only a few approaches have any potential for assessments of the water requirements for non-flowing aquatic systems, such as floodplains, wetlands, including estuaries, and lakes, and for local human livelihood. The near absence of such methods represents a serious gap in the field of EFR's. In order to provide an integrated assessment of the suitability of environmental flows to safeguard downstream ecosystems and services, this report presents a description of river functions and their relation with river flow.

The use of *ecotopes* is a relatively new approach in setting an EFR, which may provide a breakthrough in the endeavour to integrate the large number of relevant factors currently required for modern river management. It provides an essential linkage between river regime and river functions, it allows for relatively easy quantitative prediction of future situations with respect to different scenarios of river flows and it has good communication capabilities to managers.

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Executive Summary

Environmental flow requirements (EFR's) are being assessed for an increasing number of rivers world-wide. Numerous methods are used, ranging from simple hydrological indices to complex, holistic procedures in which not only the ecological water needs are assessed, but where also the local demands of human communities along the river are taken into account. This report provides an integrated approach to the assessment of environmental flows. It reviews the existing methods and concludes that the vast majority of these methods tend to narrowly focus on the instream ecological features of riverine systems. Currently, only a few approaches have any potential for assessments of the water requirements for non-flowing aquatic systems, such as floodplains, wetlands, including estuaries, and lakes, and for local human livelihood. The near absence of such methods represents a serious gap in the field of EFR's.

Findings relevant for managers

In order to provide an integrated assessment of the suitability of environmental flows to safeguard downstream ecosystems and services, this report presents a description of river functions and their relation with river flow. It clearly shows the paramount role of the dynamic flow regime for the maintenance of these functions. Although often forgotten, also many coastal ecosystems and their functions are depending on the flow of freshwater. These functions are therefore included in the river functions list and should inspire river managers to interact more closely with their coastal counterparts.

Evidently, EFR's should not a priori be limited to a specific aspect of the river regime, such as a minimum or guaranteed low flow. Instead, the full range of the river dynamics should be taken in consideration, which can be described in four classes: annual flow variability, seasonality, extreme events and smoothness. Linking these flow parameters with functions provides a truly integrated picture and makes the rather broad over-all objectives of river management, such as ecosystem integrity and sustainability, more tangible.

There is no integration without prioritization: although everything needs to be considered, at the end choices have to be made. How these decisions are made are beyond this research, how all relevant information can be brought to the decision makers does belong to the scientific domain. One of the least developed fields in EFR is the way to assess and express the needs and requirements of local people living downstream. The function approach can be effectively used in a participatory rural assessment (PRA), provided that the participants have an open mind towards an iterative process in further refining the *real* essential functions of the river.

Scientific spin-off

In this context, the use of *ecotopes* is a relatively new approach in setting an EFR, which may provide a breakthrough in the endeavour to integrate the large number of relevant factors currently required for modern river management. It provides an essential linkage between river regime and river functions, it allows for relatively easy quantitative prediction of future situations with respect to different scenarios of river flows and it has good communication capabilities to managers.

Suggestions for future research

The scientific foundation of the ecotope approach needs to be improved and tested in the field.

The development of the framework for the assessment of human welll-being in relation to environmental flows needs to be tested in different field situations.

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Environmental Flow Requirements: an integrated approach for river and coastal zone management

Marcel Marchand (editor)

June 2003

Preface

'Don't it always seem to go
that you don't know what you got
'till it's gone…'
Joni Mitchell

Man's relationship with rivers is as old and troublesome as mankind. Rivers have brought prosperity and havoc. Man has reaped the benefits, sometimes up to the last drop of water. From the cradle of civilization to the destruction of Iraq's marshes, the Euphrates and Tigris tell the story of how it once was and how it should not end. Virtually no river in the world is without some sort of regulation. The only question is: how much more water can we afford to divert for our own purposes without permanently loosing the other, less tangible values of rivers? This report addresses this question in a rational way: if we are willing to share the water with other life forms that are dependent on them, how can we make this argument strong enough in the water allocation debate? Is there a way to calculate the water needs of all river functions and values so that real trade-offs can be made? In fact, there is. The tools and methods are there. The knowledge is at hand and the data can be collected. It is only time that is running out.

Contents

1 Introduction

1.1 Background

Fresh water flowing into the sea has for a long time been considered a wastage of a precious natural resource. Water has an economic value and it should be exploited for the benefit of people, their subsistence and economic welfare. Many uses and users compete for water, especially in semi-arid regions, e.g. for irrigation, industries, domestic uses, hydropower and navigation. By constructing dams and weirs and by abstracting large amounts of water, river managers have tried to deal with the increasing demands. Recently, however, people started to realise that these river developments result in negative impacts on downstream areas in both an ecological and social sense. This led to the awareness that a certain amount of water needs to remain flowing in the river.

This awareness forms a new challenge for river management as an extra demand is now competing for the scarce water resource. Internationally this awareness is reflected in the Global Dialogue on Water, Food and Environment, which has started in the wake of the Second World Water Forum of March 2002 (see box 1).

The amount of the original river flow regime that needs to flow down the river in order to maintain specified valued features of the river ecosystem is generally referred to as the *Environmental Flow Requirement (EFR)*. The term Instream Flow Requirements is used as well, to emphasise the fact that it concerns water that remains within the river ecosystem and is not withdrawn to be used elsewhere outside of the river ecosystem.

Whereas the demands for irrigation, navigation, industries and other water users can be assessed relatively straightforward, there is still much confusion about what an EFR should comprise. The practice of EFR's began as a commitment to ensuring a 'minimum flow' in the river, often arbitrarily fixed at 10% of the main annual runoff (World Commission on Dams, 2000). But more and more scientific evidence and experience is available that questions the 'minimum flow' approach and there is now a general opinion that for safeguarding essential downstream environmental conditions the dynamics of the river flow should be taken into account. Several EFA methods have been developed over the years, that acknowledge the complexity of the flow-environment relationship. Reviews (e.g. King *et al.*, 1999, Dunbar *et al.*, 1998, Jowett, 1997) generally identify four types of EFA methods (see Chapter 3). Each type of method has its own strengths and weaknesses. This raises the question which method is appropriate in a certain context. Some methods are quantitative by nature (hydrological and hydraulic methods). They determine environmental flows based on flow records. These methods, however, leave largely implicit the river-ecosystem functions for which these flows are required. In other words the method is not transparent. Other methods (holistic methods) try to include all functions of the river-ecosystem, but are usually based on expert judgement and are therefore difficult to reproduce. Hence, there is not one method that comprises all river-ecosystem functions in a quantitative way with explicit and scientifically justified links between the functions and required flows.

Box 1: Global Dialogue on Water, Food and Environment – source Dialogue Proposal November 2001

"Following the World Water Vision and Framework for Action process that ended with the Second World Water Forum in March 2000 in the Hague, many felt that there had been insufficient interaction between the agricultural specialists and the environmental experts. In fact, the "Vision for Water and Nature" and the "Vision for Water for Food and Rural Development" show widely diverging views on the need to develop additional water resources for agriculture and the benefits and costs that such development would have. To a very large extent, ongoing activities are still organised on a sectoral basis.

Many feel that resolving the differences between these sectoral views is one of the key challenges facing society at the beginning of the twenty-first century. The water crisis of the late twentieth century was defined by the lack of access to water for domestic purposes. In the early twenty-first century, increasing competition for water will further exacerbate domestic water problems, and add a host of other difficulties related to food and environmental security. Mismanagement of this crisis will mean that a fewer people will have access to safe water, an increase of poverty, and deteriorating health standards of vulnerable communities.

Given that irrigated agriculture is the dominant user of water withdrawn form nature for human purposes, the question is how much more water can be withdrawn without causing irrevocable damage to the ecosystem. The agriculture sector asserts that 15-20 percent more water will be needed in 25 years time for agriculture to maintain global and national food security. This increase can only be achieved when significant improvements in irrigation efficiency can be obtained. The sector feels that given this situation, the dialogue should focus on options to achieve this in an environmentally sound and sustainable way and to realise food security to the poor as well. Others feel that irrigation expansion is not an option because of high social and environmental costs, and that there are other water options to produce enough food. At stake are the size and nature of both local and international investments that are necessary to grow food for a growing population, provide sustainable livelihoods for the rural poor and maintain the quality and integrity of the environment.

As one of the key issues that need consideration in the Dialogue is defined:

Assessment of (minimum) water requirements – allocation of water over uses.
Not enough is known about how much and when ecosystems need water. To some extent this goes for other uses too. Assessing requirements better will be a basis for allocation of water over users/uses."

1.2 Objective of the ENFRAIM study

In May 2001 a two year research project was started under the umbrella of Delft Cluster that intended to explore the opportunities to further develop the environmental flow concept for river management purposes. It was entitled Environmental Flow Requirements as an Aid for Integrated Management (acronym: ENFRAIM). The main objective of the ENFRAIM project was *to develop the concept of Environmental Flow Requirements into an adequate tool for integrated river and coastal management.*

To this end a number of research questions were formulated, that have been grouped into two main questions:
1. to what extent can the EFR concept be effectively used to safeguard essential downstream functions and values?; and
2. how can the integration of riverine and coastal processes and management be optimized?

Integration plays a key role in this research as it reflects the perception that modern policy making should take into account as much relevant aspects as possible. Assuming that many environmental flow assessments are geared to only a limited number of objectives which restricts their usefulness in integrated management, could it be possible to increase their scope by incorporating items such as:
- water quality aspects of the river;

- social and economic river functions;
- morphological changes in the river;
- river flow impacts on deltas, coastal, estuarine and marine environments

The dilemma of integration is its complexity. Providing information on all these subjects generates a too large database for managers to handle. The scientific challenge therefore exists in the search for suitable aggregations and classifications that provide meaningful information on which policy makers can make their decisions.

1.3 Project organisation and products

The project was executed by a group of researchers from different institutes (see table 1.1), covering a wide range of disciplines and expertise needed to address the research questions. As the project developed it became clear that its objective was rather ambitious, considering the great variety of river environments, differences in geographic and social settings and complexity of the river environment. There was a constant dilemma between exploring the different aspects of environmental flows, leading to divergence and detailed analysis, and the search for generic approaches and methods that could guide flow assessments for any particular river setting. It resulted in a number of products, each dealing with a specific part of the study objective (see table 1.2 below). This report provides the reader with a concise overview of the project results, arranged in such a way that it highlights the main findings and conclusions.

Table 1.1: list of ENFRAIM researchers, contributing partners and their affiliation

Prof. M.F. Bari	Bangladesh University of Engineering and Technology
Prof. ir. E. van Beek	Delft University of Technology / WL|Delft Hydraulics
Ir. A. Crosato	WL|Delft Hydraulics
Drs. H. Duel	WL|Delft Hydraulics
Ir. M. van Eupen	ALTERRA
V. Gangaram Panday	Delft University of Technology
Ir. J. A. G. van Gils	WL|Delft Hydraulics
Ir. S. Groot	WL|Delft Hydraulics
Dr. L. Higler	ALTERRA
Drs. M. Marchand	WL|Delft Hydraulics
Ir. K. S. Meijer	Delft University of Technology / WL|Delft Hydraulics
Mukteruzzaman	Bangladesh University of Engineering and Technology
M. Naz	Bangladesh University of Engineering and Technology
Ir. W. E. Penning	WL|Delft Hydraulics
Dr. M. Rozemeijer	WL|Delft Hydraulics
Dr. M. Vis	WL|Delft Hydraulics
Ir. M. van der Wegen	IHE
Dr. HP. Wolfert	ALTERRA

Table 1.2 ENFRAIM project main products:

1. **ENFRAIM Review**
   W.E. Penning
   Delft Cluster Report 06.02.04-01, August 2001
2. **Environmental flow requirements as an aid for integrated management**
   M. Marchand, E. Penning, K. Meijer
   published in the conference proceedings of Cape Town, 3-8 March 2002
3. **Management of Rivers for Instream Requirement and Ecological Protection – Baseline report**
   M. F. Bari & M. Marchand
   BUET-DUT Linkage Project Phase III, Dhaka, July 2002
4. **Final Report ENFRAIM**
   M. Marchand (ed.)
   Delft Cluster Report 06.02.04-03
5. **ENFRAIM Thematic Studies Report**
   R. Vis (Ed.), A. Crosato, K. Meijer, S. Groot, J van Gils, M. van der Wegen
   Delft Cluster Report 06.02.04-02
6. **Water quality monitoring - A manual for simple quality assessment in developing countries**
   L. Higler
   Alterra
7. **Internet page ENFRAIM project: http://enfraim.wldelft.nl**
8. **Considering people's well-being in the assessment of environmental flow requirements.**
   K. S. Meijer
   Paper XI World Water Congress: Water Resources Management in the 21st Century. Madrid, 5-9 October 2003.
9. **Training material on river-coast interactions**
   pre-IAHR course, Tessaloniki
   R. Vis & M. Marchand
10. **Training material: CD-ROM with database, literature and powerpoint presentations**
    W.E. Penning
11. **Using the ecotope concept in environmental flow assessment: case study in the Surma-Kushiyara river system, Bangladesh**
    M. Marchand, M.F. Bari, Mukteruzzaman, H. Wolfert, W.E. Penning & K.S. Meijer,
    in prep. (to be submitted to: J. River Basin Management)
12. **Institutional arrangements for effective protection of the coastal environment in the district of Ernakulam, Kerala**
    V. Gangaram Panday
    MSc. Thesis
    Delft University of Technology

2 The EFR concept

2.1 Definition

An environmental flow requirement is that part of the original flow regime of a river that should continue to flow down in order to maintain specified valued features of the river ecosystem. The river ecosystem is seen as all components of the landscape directly linked to the river, and their life forms. It includes the source area, the channel from source to sea, riparian areas, the water in the channel and its physical and chemical nature, associated groundwater in channel and bank areas, wetlands either through surface or subsurface water, floodplains, the estuary and any near-shore environment that is dependent on freshwater inputs (King *et al.,* 1999). The study that is needed to arrive at a certain flow requirement is called an environmental flow assessment (EFA). In the literature also other terms are used that are more or less similar to the EFR concept, such as *minimum flow*, *managed flood* and *river flow objective* (see box 2).

Box 2: other terms used for environmental flows

Minimum flow
A certain set all year minimum had to remain in a stream, all higher flows were available for offstream use (King *et al.*, 1999). Until about 1973 minimum flow was the prevailing term for the concept of environmental flows. Nowadays this term is hardly used anymore because it seemed to imply a fixed value, which paid no attention to the natural flow variability and the EFR as a comprehensive flow regime, which is dynamic over time. (King *et al.*, 1999).

Managed flood
A controlled release of water from a reservoir to inundate a specific area of floodplain or river delta downstream to restore and maintain ecological processes and natural resources for dependent livelihoods undertaken in collaboration with stakeholders. This is distinct from sudden, unplanned releases sometimes made from reservoirs to prevent dam failures without warning downstream communities (Acreman *et al.*, 2000).

River flow objectives
This term is used in the UK (Dunbar *et al.*, 1998) but there seems to be no equivocal definition. Two alternative definitions are:

1. The flows, which need to be protected to ensure the river can support the abstraction requirements placed upon it without compromising important ecosystems (Environment Agency Corporate Strategy, in Dunbar *et al.*, 1998);
2. The flows which are needed to sustain the desired ecosystem, to meet abstraction requirements, and to support important in-river uses (Petts *et al.*, 1996, in Dunbar *et al.*, 1998).

This term seems to be more encompassing than the term environmental flow requirement, it is the objective for flows when both environmental flow requirements and abstraction demands are combined in an integrated river management.

An *instream flow* is often regarded synonymous with environmental flow. It assumes that only the flow of water in the river channel contributes to the maintenance of a river environment (ecosystem), whereas out-of-stream flow does not. Within the river corridor, ecosystems can be defined, such as isolated oxbows, the floodplain and fringing wetlands, that are influenced by the river flow, e.g. via groundwater flows, flood flows, creeks and natural channels. As long as these connections are part of the natural river environment we propose to include the river water requirements of these ecosystems as part of the instream flow requirement. An instream flow can also be defined for navigation requirements or for hydro-power, as these functions are dependent on (part of) the river ecosystem.

In this report the term environmental flow is used instead of instream flow in order to avoid any ambiguity with respect to a narrow interpretation of the flow, i.e. we are not only interested in the flow within the river channel, but in the full range of flow conditions that may influence ecosystems in the river corridor.

2.2 Objectives for EFR

Setting the objectives for an assessment of flow requirements is a critical step in the whole procedure. After all, this greatly determines the type of method that should be used and it also plays a key role in the debate of the acceptability of water withdrawals. In practice, there seems to be two ways of setting objectives. Firstly, an objective may be set, the EFR to achieve it described, and the water for abstraction calculated. Alternatively, the consequences of manipulating the flow regime in a variety of different ways may be predicted, so that a range of possible river and resource conditions can be considered. In the first, top-down approach the management objective is set up front, in the second, bottom-up approach, it emerges at the end as the most acceptable option among the several options for river conditions considered (King *et al*. 1999).

Both approaches have their advantages and disadvantages, but neither of them provides a solution on how to make broad objectives such as ecosystem integrity and sustainability more operational and meaningful. One could argue that the bottom-up approach is the best way to get an insight on what these concepts mean for a specific river. By estimating the effects of a wide range of river flows a picture may emerge of how the river ecosystem reacts and changes from a healthy and sustainable state towards a degraded state. But still: can ecosystem integrity and health be defined in an unambiguous manner? It cannot, but choices will be made, either by governments or other authorities. Often a government will have a certain water policy on which they decide what is more important and what is less. But decision makers need to have information on which their priorities are based. This information pertains both to the interests of stakeholders and the carrying capacity and services that the river and its ecosystem provide. Within the framework of this research the underlying principles and knowledge is unravelled that address both the ecosystem functions and the livelihood of local people who are often dependent on these functions and services. There is a special chapter on the outcome of the research regarding the relation between livelihood and environmental flows (Ch. 6).

2.3 Underlying assumptions

Although a considerable body of literature exists on environmental flow methodologies, surprisingly little exists on the philosophy underpinning these. Nevertheless, questions abound, among those involved in such flow assessments, from seemingly simple ‘is there *spare* water in a river?’ to obviously complex ones regarding the importance of variability and predictability of flow and of ecosystem characteristics such as resilience and resistance (King *et al*., 2000).

There has been considerable discussion among ecologists about defining ecosystem integrity, health, sustainability and resilience. In their paper on ecosystem integrity, De Leo & Levin (De Leo and Levin, 1997) define two different approaches that seem to be relevant in view of the various EFR methods. Starting from the distinction between the reductionist and holistic approach, they define two different definitions of integrity:

1. strict attention to the structural aspects of ecosystems, as represented primarily in species composition (the 'reductionist approach'), leads to a definition in which the loss of even one species or the damage of a link between some components implies a loss of integrity, because the ecosystem is no longer 'complete'.
2. on the contrary, from the perspective of functional integrity (the 'holistic approach'), redundancies within functional groups make the biological composition less relevant.

Of course these approaches both have their merit, and as structure and function are linked, a combination of both approaches may be opted for. The use of keystone species, whose removal may engender dramatic changes in the structure and functioning of its biological community, could be used to link the two approaches.

Accepting the concept of an Environmental Flow Requirement, which substantially differs from the natural flow, basically implies that one chooses for the second option: there are redundancies within the river system (be it species or other components) which can be lost without disturbing the functioning of it. In other words: *there is spare water in rivers* (King *et al*., 2000). In their Building Block Method, King *et al*. (2000) provide three main practical justifications for this assumption:

- the naturally highly variable flow regimes in most rivers imply that any species which persists in such rivers must be able to survive during years when there is much less water than average;
- all rivers do not necessarily need to be maintained in a near pristine condition;
- major floods cause structural damage to rivers, and carry water that can be intercepted by dams and used to augment low flows.

The main question then becomes: which are these redundancies, what are the key species, linkages or processes that need to be conserved? This makes the assessment of an EFR both a scientific and political endeavour: society should decide what the appropriate status of the river should be and science then should provide the right flow conditions to maintain this status. Of course, in reality this process is (or should be) more iterative than described here, as science also provides input for the appropriate status.

A sound decision therefore need to be based on scientific information that provides the relationships between flows and the ecosystem functioning as a whole. Ideally, this information should be given in a form that can be used in trade-offs. For instance, fishery production as a function of discharge. This function can be a straight line, but more likely it may have a certain threshold in it, beyond which the entire fisheries collapses. The same can be true for the entire ecosystem integrity: how much redundancy can we afford to lose without pushing the system to the edge of some irreversible and catastrophic change?

3 Review of existing methods

3.1 A global perspective

The methods first developed (in the 1960s) were based on the judgement of biologists, but were soon followed by simple methods using some measure of the unregulated stream flow (Gordon, McMahon, and Finlayson, 1992). A growing number of countries now recognise the need for EFR's and are either searching for or developing suitable methodologies to assess them or adopting tried and tested approaches from elsewhere. The Instream Flow Incremental Methodology (IFIM) has long enjoyed legal status in America. In Spain, 10% of the mean annual run-off of a river should be released from dams as environmental flows, which although probably insufficient to sustain the downstream environment, at least acknowledges the need for environmental flows. It is important, however, to remember that even the most successful EFR will only partially mitigate against the effect of a dam or diversion on a river (King *et al.*, 1999).

In countries such as the United States of America, the need to manage rivers in a manner protective of biological diversity has driven many debates over instream flow allocations in recent years. For the most part, the success of a negotiation has been judged on the guarantee of a minimum flow to support fish and other aquatic organisms. The passage of major federal environmental laws in the late 60's and early 70's, such as the Wild and Scenic Rivers Act, the National Environmental Policy Act and Endangered Species Act, has brought greater scrutiny to the potential impacts of water developments. And river flow restoration is being pursued in hundreds of river basins in the US presently, the controlled flood experiment in the Grand Canyon of the Colorado River being one of the most well known examples (Richter, 2002). Although these developments show that there is an increased awareness for the need for EFR's, there are also fierce debates and lawsuits on various rivers with regard to the provision to set flows for ecological purposes (see table 3.1). A striking aspect of most of these examples is the crucial role of the Endangered Species Act, which at one hand proved to be very important in legalising instream flows, but on the other hand shows the difficulty of enforcing EFRs for preserving entire river ecosystems in absence of an endangered species. It also may explain why the USA have not invested much effort in exploring holistic type methodologies and the overwhelming application of habitat simulation methods, such as IFIM (Tharme, 2002).

The desire to conserve an entire range of species dependent on a river system has posed a problem for resource managers, because it is virtually impossible to manage a river in a way that optimizes conditions for all species at all times (Hunt 2000b). In order to overcome this problem, the attention has shifted from the minimum flow approach to an approach that uses the 'natural' regime of the river as a starting point, for instance the Range of Variability Approach, focusing on the role of hydrological variability in sustaining riverine ecosystems (Richter *et al.*, 1997, Poff *et al.*, 1997).

Table 3.1: examples of lawsuits and debates on water rights for ecological protection in the US

Platte river, Nebraska	March 1997: Final decision in water rights in Platte River delayed until 1998 A coalition of irrigation groups, utilities and natural resource districts is contesting the request for an instream flow on the Platte river. The Game and Parks Commission filed in 1994 for a state water right to reserve the remaining flows in the Platte (those not already used for irrigation and other uses) to maintain fish and wildlife habitat. Experts from both sides have presented evidence for their case.
Columbia River, Oregon	July 1999: Conservationists challenge huge new Columbia River water withdrawal in court Three conservationist groups have sued the US Army Corps of Engineers for failing to protect imperilled salmon and steelhead in eastern Oregon. A new water withdrawal is proposed by a large corporate farm, Inland Land Co., to irrigate lands that currently provide valuable habitat for several rare wildlife species.
Canadian River, Texas	December 1998: Arkansas River shiner not to be listed as a endangered species; High Plains Water District officials pleased with decision The US Fish and Wildlife Service decided not to list the Arkansas River shiner as an endangered species under the Endangered Species Act. Listing the Arkansas River shiner as threatened, rather than endangered will have fewer restrictions on the surface and groundwater use.
Klamath River, Oregon	May 1996: Supreme Court species protection case may alter intent of law The U.S. Supreme Court will hear arguments in an Oregon case which may determine whether people with an economic stake can use the nation's most powerful environmental law, the Endangered Species Act, to accuse the federal government of overprotection of a species. The case involves two ranchers in the Klamath River Basin who sued the U.S. Fish and Wildlife Service in 1992 when it curtailed their irrigation water to protect two endangered fish.
Missouri River	July 1995: Corps scraps proposal for Missouri River flows **After two years of public debate that included some two dozen hearings, the Army Corps of Engineers has scrapped a controversial plan that would have mimicked natural springtime flood surges of the Missouri River to enhance endangered species habitat. While the plan was generally embraced by upstream states that rely on recreational tourism, downstream interests opposed the move as being detrimental to river navigation and agriculture in general.**
Upper Snake River, Idaho	November 1995: Idaho irrigators to file suit against salmon restoration **A group of Upper Snake River Valley irrigators is expected to file suit this month seeking to halt a federal proposal to use some 427,000 acre feet of Idaho water to help flush migrating salmon into the Pacific Ocean. In a notice of intent to sue, a group called the 'Committee of Nine' contends the water transfer is not based on 'the best scientific data' on how to restore endangered salmon runs.**

Source: US Water News Litigation/Water rights archives (1995-2003)

In Europe the enactment of environmental flow requirements varies between the countries. Often the (re-)licensing of dam operations provides the main framework for executing EFRs (e.g. in Norway the allocation of instream flows is done with respect to new licences, renewal of old licences and in response to the new Water Resources Act, which opens for a more flexible treatment of instream flows (Brittain, 2002)). And although the European Union Water Framework Directive has clearly defined environmental standards for entire watersheds, including criteria based on biological indicators, on physico-chemical characteristics and hydro-morphological conditions, this has up till now not resulted in a European standardised method for addressing environmental flow requirements.

In Australia most applications thus far, especially early on, centred on the use of expert panel approaches such as the Expert Panel Assessment Method (EPAM) and more advanced Scientific Panel Assessment Method (SPAM), and the Holistic Approach. Increasingly sophisticated, diverse methodologies have emerged, including the Flow Restoration

Methodology (FLOWRESM) and the Benchmarking Procedure, especially suitable for poorly studied systems (Tharme, 2002).

In contrast with developed countries, in the vast majority of developing countries environmental flow assessment has received significantly little attention: only 11% of the developing countries are recorded as applying environmental flow methods (Tharme, 2002). This applies even to semi-arid and arid parts of the world, where the availability, quality and sustainability of freshwater resources play a crucial role in socio-economic development (King et al. 1999). A notably exception forms South Africa, which can be regarded as being in the forefront of countries developing new methods for environmental flow assessments.

In South Africa the National Water Act (NWA) of 1998 provides the legal framework for setting environmental flows. One of the key provisions of the NWA is the recognition that the water resources require protection. This is formalised in the 'Reserve' concept the definition of which is 'that quantity and quality of water required i) to satisfy basic human needs for all people who are, or who may be, supplied from the relevant water resource, and ii) to protect aquatic ecosystems in order to secure ecologically sustainable development and use for the relevant water resource'. Different levels of resource use, resource protection and ecosystem health need to be provided for and it is therefore necessary to classify each water resource for which the Reserve is to be determined. These are reflected in the so-called Ecological Classes in the form of classes A to F where A represents reference conditions and F represents a critically modified system. The classes are usually defined following a process consisting of sequential steps. The South African Reserve concept within the context of the water law is an ambitious undertaking and although more than 50 environmental flow assessments have been undertaken, no formal implementation of these assessments or Reserves have taken place yet (Louw *et al.*, 2002). Major problems identified in implementing the Reserve include:

- limited liaison between groups working on the quality and quality method development leading to inconsistent visions and approaches
- limited capacity of human resources to apply the Reserve, both within the Government Departments and the scientific community;
- continuous terminology changes leading to confusion and loss of faith in the procedures
- insufficient monitoring, verification and testing of methods.

Notwithstanding these difficulties the South African Water law can be considered as a most prominent new legislation which recognises environmental flows as a basic requirement for sustainable development of rivers. It has prompted the development of new holistic methods, such as the Building Block Method, which to date remains one of only two routinely applied flow methods in the world for which a manual has been written (King et al., 2000), the other being IFIM (Tharme, 2002).

These examples clearly show that although EFR's are gaining momentum in many countries, there is still confusion and controversy over both the ecological and socio-economic arguments to set aside a part of the river's water resources for downstream functions and uses. Many cases highlight the intricate web of socio-economic impacts and demonstrate that altering environmental flows is a matter of redistributing costs and benefits with winners and losers (Hirji & Panella, 2002). Evidently, although preparing EFRs for specific objectives, such as endangered species, may have a legal basis in certain countries (such as the USA), there is a general tendency to address more holistic objectives such as ecosystem integrity, biodiversity, livelihood sustenance and river health. At the same time it is crucial that these concepts need to be made explicit in their supposed benefits, making trade-offs in decision making possible.

3.2 A concise overview of methods

There are well over 200 individual methodologies for environmental flow assessments (Tharme, 2002) and it would be unfeasible to describe them in this report. Many review publications are available in the literature, such as Tharme (1996 and 2002), Dunbar *et al*. (1998), Jowett (1997), King *et al* (1999), Smakhtin (2001) and Penning (2001). A short characterisation of the main methods is given below.

3.2.1 Hydrological methods

Hydrological methods rely mainly on available hydrological data (e.g. long term monitoring, historical monthly or daily discharge records) and are also termed 'look-up' methods (Petts 1996) that aim on determining a 'minimum' environmental discharge, which is vital to the ecological functioning of the river. There are at least 15 frequently referenced, hydrology-based methods, of which several are fairly specific focussing on a certain region or context (King *et al.* 1999). The most commonly used hydrological method is the *Tennant method* (Tennant, 1976). It specifically links average annual flow to different categories of instream habitat condition.

The *Flow Duration Curve Analysis* (FDCA) uses historical flow records to produce curves displaying the relationship between the range of discharges and the percentage of time that each of them is equalled or exceeded. Discharges representing specific flow percentiles are calculated from the curves and then used in a variety of ways to produce specific environmental flow conditions. The method is generic by nature with respect to the functions it can cover (e.g. one can use it for environmental conditions which favour navigation as well as salmonid fishery).

The *Range of Variability Approach* (Richter *et al.*, 1997) is specifically developed for situations when conservation of native biota and ecosystem integrity are management objectives. It aims at providing a comprehensive statistical characterisation of ecologically relevant features of the flow regime, focusing on the role of hydrological variability in sustaining riverine ecosystems.

The *7Q10 method* (7 day low flow event over a 10 year period), is used mostly in the eastern and southeastern USA when water quality issues predominate (King et al., 1999). This method is used as part of a Total Maximum Daily Load (TMDL) assessment to determine a waterbodies assimilative capacity. It is based on flow measurements (Anonymous 2001).

3.2.2 Hydraulic rating methods

The hydraulic rating methods, of which the wetted perimeter method is considered, are developed and applicable specifically for assessing aquatic habitats for riverine fish. They can be described as single, river channel cross-section methods that use changes in various single hydraulic variables, such as wetted perimeter or maximum depth, as a surrogate for habitat factors limiting biota, to develop a relationship between habitat and discharge for environmental flow recommendations. One of the most commonly used hydraulic methods considers the variation in wetted perimeter with discharge (Reiser and Wesche 1989). Hydraulic rating methods represent the precursors of more sophisticated habitat simulation methods that use hydraulic data as well as associated microhabitat and biological information.

3.2.3 Habitat simulation methods

Habitat simulation methods evolved out of the previous types of EFAs to create a better understanding of habitat requirements. These methods are assessing the instream habitat in terms of hydraulic variables, such as depth, average column velocity and benthic shear stress. Hydraulic variables are combined with information on the suitability of microhabitat conditions for particular species, life stages or assemblages to predict optimum discharges. When this is done for a range of flows it is possible to see how an area of suitable habitat changes with flow. Jowett (1997) states that since habitat methods are quantitative and based on biological principles, habitat methods are considered (in the USA at least) to be more reliable and defensible than assessments made by other methods. One of the most famous habitat methodologies is the *Instream Flow Incremental Methodology* (IFIM) (Anonymous, 2001; Bovee, 1982) originally developed by the Instream Flow Group of the US Fish and Wildlife Service, Colorado in the late 1970s and adapted by many others (King *et al.* 1999)

3.2.4 Holistic methods

Holistic methods are all based on the concept that the complete riverine ecosystem (including floodplains, estuarine and offshore coastal systems) is affected by the complete flow regime, so an adequate description of these flows in terms of magnitude, duration, timing and frequency and their incorporation in the regulated flow regime should allow the biotic characteristics and functional integrity of the river to persist (Arthington *et al.* 1992). It is further assumed that some baseflows and floods within the complete flow regime are more essential than others for maintenance of the riverine ecosystem.

As a result of the multidisciplinary nature of holistic methodologies, many data requirements and types of expertise are required. Comprehensive hydraulic and hydrological data are essential, together with data on biotic features and data on the needs of the local people, which depend on the river for their livelihood (the PAR) are also essential.

A few methods have become widely known. These are the South *African Building Block Methodology* (BBM) (King *et al*., 2000) and the *Australian Holistic Approach* (Arthington *et al.* 1992). DRIFT (*Downstream Response to Imposed Flow Transformations*) later evolved from the BBM. BBM and the Australian Holistic Approach rely on a bottom-up approach to construct a modified flow regime based on month-by-month and element-by-element basis, where each element represents a well-defined feature of the flow regime intended to achieve particular, well motivated ecological, geomorphological, water quality or social objectives in the modified riverine ecosystem. They require intensive baseline data collection, followed by multidisciplinary input in a workshop situation.

3.2.5 Combined methods and other approaches

A fairly high number of methods representing some combination of hydrological, habitat-discharge and/or holistic approaches have been developed and applied across the world. The methods range from the country specific, combined hydraulic and *biotic Basque Method*, through to more broadscale approaches, such as the *Habitat Evaluation Procedure*-based framework (Duel *et al*., 1994) and use of physical biotopes/functional habitats. The most commonly applied combination EFM was recorded as *the Managed Flood Release Approach* of Acreman et al. (2000), or similar approaches based on experimental flow releases (Tharme, 2002).

3.3 Conclusion

The review of methods shows a picture of great diversity and on-going developments of which the end is not yet in sight. It illustrates that the need for preserving downstream river environments is a world wide issue. It also shows that methods are being developed for specific environmental conditions and social/legal requirements which imply that they often cannot be simply applied in other countries. In other words no single EFR method is perfect under all conditions.

The vast majority of methods tend to narrowly focus on the instream ecological features of riverine systems. Currently, only a few approaches, mostly holistic ones, have any potential for assessments of the water requirements for non-flowing aquatic systems, such as floodplains, wetlands, including estuaries, and lakes. The absence of such methods represents a serious gap in the field of EFR’s (King et al. 1999). In order to assess the scope of the current EFR methods more systematically, in this research a function approach is used, which is elaborated in the next chapter.

4 A function approach for EFR's

4.1 A generic classification of river functions

The function approach to environmental problems has gained momentum in the late seventies and early eighties when a linkage between ecological concepts and economic theories and evaluation methods was considered essential to solve environmental problems. The main purpose was to provide the ecological basis for a dialogue between ecologists and economists in order to structurally integrate environmental constraints in economic evaluation and accounting procedures (De Groot, 1994). This argument has not lost its importance as trade-offs between economic development and environmental preservation remain to play an important role in decision making even now the concept of sustainable development has reduced the discrepancy between the two. And especially for water allocation decisions in river management the weighing between demands for (upstream) economic activities and those for downstream environmental preservation requires insight in the various trade-offs.

Considering the ultimate goal of river management, being sustainable use and development, this implies striving towards economic efficiency, ecological integrity and social equity, including the rights for future generations (Young 1992). Putting this in the water allocation perspective this could be translated into the following criteria:

- water should be allocated to those economic activities that provides the maximum benefit for man and should not be spilled;
- the river regime should be maintained as much as possible to safeguard the river ecosystem integrity; and
- upstream and downstream users should have an equitable share of water resources.

Environmental flow requirements can become an important management tool in this respect as it is a tool in defining downstream requirements for economic purposes and the ecosystem for the benefit of the people that are dependent on the river. As the tool is to be used in decisions between upstream and downstream water allocation it should be transparent and objective in such a way that it can be acceptable for all parties. To reach this objective the function approach (often referred to as 'function evaluation') is considered to be highly relevant and instrumental in a similar way as it has been proved successful in other domains of environmental problems (Van der Maarel & Dauvellier, 1978; De Groot, 1994; Slootweg et al., 2001)

The function approach finds its theoretical roots in the man-environment model (see Fig. 4.1). This model provides basically four entrances for developing a classification of environmental relationships, viz. 'man', 'environment', 'functions' and 'interventions'. The choice for the functions entry can be underpinned by the following arguments:

- we are interested in the *relationship* rather than the conditions in itself of the environment or human society. It is through the (in)ability of fulfilling the human needs that environmental problems are defined rather than the environmental condition *per se*.

- a listing in terms of interventions seems less relevant. Whether an EFR is formulated for a river with a dam or for a water abstraction project is rather irrelevant for the downstream users: the flow needs remain the same. This however does not mean that implementing an EFR is not dependent on the type of intervention. On the contrary: the engineering dimensions of the intervention often determine the margins within an EFR can be formulated.
- an enumeration in terms of environmental conditions would lead to EFRs for specific species or ecosystems, which ultimately would lead to an endless list, or to a selection of limited objectives. Many EFR methods do exactly this (especially for Salmonid fish species), which can have a high policy relevance, but leave the question unanswered what to do with 'the rest'.

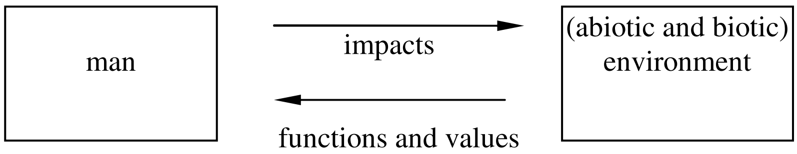

Figure 4.1. Man-environment relation in its most simple form

The advantage of the function approach is that it provides insight into the multifunctionality of resources. By identifying the functions, the relevant units of measurement can be identified and decision-making can be based on a more profound understanding of the role the biophysical environment plays for human society (Slootweg et al., 2001).

The next step in the function approach is the definition of the river functions. In line with the definition of environmental functions river functions are defined as goods or services that satisfy human needs derived directly or indirectly from the river ecosystem. The *goods and services* include not only harvestable products but also refers to other benefits of natural processes (i.e. the services), such as the capacity to recycle waste. The *human needs* should be defined in the broadest sense possible, i.e. not limited to material prosperity provided by marketable goods and services, but also including physical and mental health and the prospect of a safe future. Also the river ecosystem is defined in a broad sense: the river ecosystem is seen as all components of the landscape that are directly linked to that river and all their life forms, including the source area, the channel from source to sea, riparian area (i.e. the longitudinal riverside strips with vegetation types that are distinct from the general terrestrial landscape), the water in the channel and its physical and chemical nature, associated groundwater in channel and bank areas, wetlands linked either through surface or sub-surface water, floodplains, the estuary, and the near-shore marine ecosystem if this is clearly dependent on freshwater inputs (King *et al.*, 1999).

Another important component of the function approach is a categorisation of functions. For reasons of transparency and objectivity in water allocation decision making, we need a method to clamp down on the risk of overlooking crucial facts of river flow requirements. Such a device is not necessarily a checklist, but a comprehensive checklist is much easier to construct than a comprehensive model or theory. If such a single list would also consist of truly homologous, well defined, mutually exclusive and relevant categories of functions, we would have arrived at something that might be generally used to avoid problems of double-counting, lost system level characteristics, irrelevancy, vagueness and un-assigned categories, that often thwart discussions and assessment studies (Marchand & Groot 1988).

Checklists may be developed by expansion, starting from a single entity, in our case 'all river functions'. Starting with this first entity, we may repeatedly apply arbitrary, but mutually exclusive dichotomies for further enumeration. Applying this method to the classification of De Groot (1994) we may come to the following scheme:

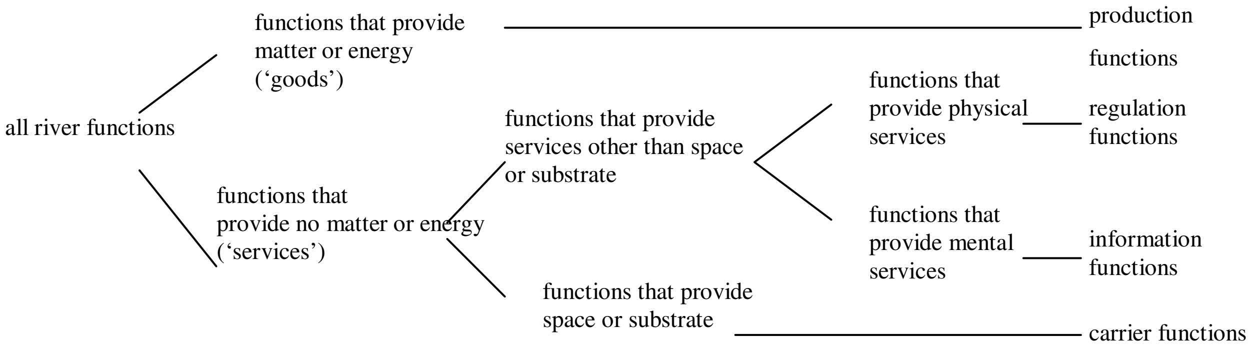

Figure 4.2: Categories of river functions based on mutually exclusive dichotomies

The above four categories of functions can further be extended to any level of detail desired. In our case, we will finalise our list by filling in a large number of possible and meaningful functional uses of the river ecosystem (table 4.1). In reality not all functions will be relevant for every river, but as we will see later, extending or eliminating relevant functions is a crucial phase in the assessment of environmental flow requirements. As the basic structure of the list does not change, it can now serve as a practical checklist for this exercise. One word of caution should be mentioned already, and that is that the list should remain homologous. Take for instance the silt catchment capacity of floodplains. This may be considered as a phenomenon whose relevancy is the maintenance of soil fertility. Then, 'maintenance of soil fertility' would be a regulation function. Further along the causal chain, however, the relevancy of soil fertility is in benefit for agriculture. Now, in order to evade double-counting, either 'maintenance of soil fertility' (as a regulation function) or 'agriculture' (as a production function) should be taken as a function.

Table 4.1: generic list of river functions

Carrier functions	Production functions	Regulation functions	Information functions
• navigation and transport • riverbank occupation • coastline stabilisation and delta formation	• water supply (industrial/domestic) • hydro-power generation • agriculture • fisheries • hunting and gathering • forestry	• purification capacity • flood mitigation • health • moderation of salt intrusion • hydrological cycle • estuarine and lagoon integrity	• gene pool • tourism and recreation • existence value

In the next sections each of the functions will be described and the relevance of EFR is briefly assessed. Each paragraph concludes with a relation in which the EFR is linked to a key process and key parameter that indicates the performance of the function.

4.2 Carrier functions

Navigation and transport

Larger rivers often are an important and sometimes the only available means of transport. A major requirement for river transport is, of course, sufficient water depth, but other factors, like high flow velocity, waterfalls and barrages without locks, and excessive growth of water weed can form important impediments for efficient transport over water. Flow requirements are not only important to provide sufficient water depth given an actual river geometry (Q-h relation), but also in order to maintain long term river bed stability. Often additional measures like river training works and dredging are needed to ensure sufficient depth in the main channel of the river.
shipping characteristics → water depth → Q-h relation → EFR ; and
shipping characteristics → water depth→ river bed aggradation or degradation → morphodynamics → EFR

Riverbank occupation:

Riverbanks, levees and associated floodplains are influenced by both hydro- and morphodynamical processes. Sometimes the changes can be quite significant, e.g. in the Gorai River (Bangladesh), where areas in the order of one hectare per river km per year are eroded and accreted (Bari & Marchand, 2002). It goes without saying that this greatly affects the livelihood of the riverine people. Many factors are involved in the morphological process, including grain size, sediment availability, discharge and flow velocity. Hence an EFR is not the only factor of the process, but on the other hand it is often the only one that can be controlled to a certain extent.
Riverbank stability → erosion and accretion→ river morphodynamics → EFR

Coastline stabilisation and delta formation

Long term coastal erosion and accretion is basically governed by two factors: sea level changes and availability of sediment. Rivers play a major role in the supply of sediment, although in some cases (e.g. the Northsea) existing sand deposits offshore may prove to be a major source reflecting the influence of rivers in the past rather than in the present. Storage dam constructions upstream have proven to be causing coastal erosion in deltas and coasts in many parts of the world. Although sediment *transport* is largely determined by water flow conditions, the sediment *availability* is determined by other factors like landuse and reservoir sinks. Therefore an EFR can be useful in erosion prevention, but its effectiveness is limited.
Coastal erosion and accretion → coastal morphodynamics → sediment transport → EFR

4.3 Production functions

Flood /Recession agriculture

In semi-arid areas, and particularly where dryland cultivation is limited by rainfall, recession farming, in which the young crops are planted in the wake of the receding water, has developed as a naturally irrigated system. Millet, garden crops etc. are grown and harvested during the post-flood period. In humid areas, floodplain agriculture is typified by rice cultivation and this still continues under semi-natural conditions with the cultivation of deep water *'floating rice'* varieties in parts of Asia (Acreman et al., 2000). Defining flow needs for flood an recession agriculture in floodplains is mostly done (if done at all) by means of rule-of-thumb. The most evident relation to be used is the extent of flooding as a function of discharge. But of course, also the timing and duration of the flood is of importance. The principal objective of flood releases from the Manantali Dam on the Senegal river is to support downstream recession agriculture. A review of the natural (pre-dam) flood regime and related recession culture indicated that recession cropping varied from 103,100 ha is wet years to almost nothing in years with negligible flooding. Flood release hydrographs were designed to enable cultivation of 50,000, 75,000 and 100,000 ha depending on the river flow in any year. Hence, it was planned that flood releases would enable an increase in the area cultivated, particularly in a dry sequence of years when under natural flow conditions there would be very little flooding (Acreman et al. 2000).
recession agriculture → cropping area → flooding extent → EFR
recession agriculture → crop yield per ha→ flood timing+ flood duration →EFR

River fisheries

Many rivers in climatically unstable areas have parallel fish faunas adapted to different climatic regimes. In general there is a fauna adapted to periods of drought, which spawns and lives within the main channel of the river, and one adapted to more normal flood regimes, which spawns and feeds on the floodplain. In addition to the permanent residents of rivers, diadromous fish occupy the inland water system for only part of their life cycle. Most river fish species require a particular flow regime to complete their life cycle in the most efficient way possible and there are, therefore, floods of different qualities relative to this reference point. But apart from the intensity of the flood (the extent), also the quality of the flood is of relevance (i.e. timing, amplitude, duration, rapidity of change, smoothness and drawdown) (Welcomme, 2002).
fish productivity → flooding extent+ 'quality of flood' →EFR

Furthermore connectivity is also very important and requires structural measures rather than an EFR (e.g. fish ladders, fish friendly sluices etc.). And of course the water quality and fishing pressure are factors that can greatly determine the actual status of the fishery.

Coastal fisheries

Coastal lagoons are transitional systems that are occupied by three main blocks of fish species. Freshwater species move into the lagoon from the inflowing rivers during flood seasons to feed when the water is mainly fresh to slightly brackish. During periods of low

flow these species withdraw into the rivers and are replaced by marine species. Marine species migrate in from the sea, often to reproduce during dry seasons when the water is primarly saline. A few species are permanently resident in the lagoon, being adapted to fluctuating salt concentrations. Some species, such as peneid prawns, mullets and milkfish have a larval phase that remains in the lagoon for at least one freshwater season (Welcomme, 2002). A reduced river inflow can cause reduced reproduction of these prawns and fishes that typically have a high market value.
fish value→ lagoon salinity →EFR

Marine fishery tend to depend on nursery areas close to the coast, which are influenced by river flows as well. This phenomenon is called ROFI: **R**egion **O**f **F**reshwater **I**nfluence, the distinctive feature of these regions being the input of significant amounts of freshwater from river sources. On a global scale it is clear that ROFI's represent an important component of the shelf-sea environment of particular concern in relation to the impact of pollutant discharges (Simpson, 1997). Perhaps the most important feature is the density driven bottom current which causes silt, detritus and larvae to accumulate in the coastal zone. For example, the Mississippi discharge is negatively associated with numbers of half year old recruits of Gulf menhaden (*Brevoortia patronus*). Discharge of the Mississippi River and the population recruitment of Gulf menhaden may be plausibly linked through the action of the river's plume and its front on the shoreward transport of larvae (Govoni, 1997). Similar relationships between freshwater, water quality and currents are found between the river Rhine and the Northsea and Waddensea.
fish recruitment→ ROFI →EFR

Livestock herding

Floodplain grasslands are grazed by livestock during dry months. Managed floodplain grazing systems have evolved under a variety of climatic regions, ranging from temperate water meadows to arid and tropical floodplains and deltas. These grazing systems mimic natural wildlife systems, with seasonal migrations from hinterland grazing during the rains to the floodplains during the dry season. The combined system can make available much larger areas of hinterland grazing, supporting considerably greater herds numbers than could be supported throughout the year on any one component. In addition, the seasonal movement of livestock has the added benefit of reducing risks of overgrazing and habitat degradation - in both areas of hinterland grazing and floodplains. The other floodplain element that is particularly significant in arid and semi-arid areas is the availability of highly nutritious browse in floodplain woodlands and riverine forests (Acreman et al., 2000). Analyses of the pastures on the Logone floodplain (Cameroun), for instance, indicate a grassland productivity of 8-10 t/ha.y, which enables a high potential carrying capacity of ca. 1-2 head/ha during the non-flood period. This is considerably higher compared to the uplands, which can carry an average of 0.2 head/ha (Marchand, 1987). Leaves, grasses, and seed pods, may also be collected as fodder for sale or used as a dry-season cattle feed (Dugan, 1990).
livestock capacity → grassland productivity → flooding extent, duration and timing → EFR

Hunting

Hunting is a major benefit to local communities along the river, both for subsistence and as an income source. Wildlife from the floodplain grasslands and forests can be used for a wide range of products among which are meat, skins, honey and eggs (Dugan, 1990). Among many communities is also has cultural and social significance. Indeed even in developed countries, the ‘minor products’ of recreation and hunting are increasingly recognised as the most valuable benefits for floodplains and are the main justification for wetland conservation and regeneration in many parts of the world, including the USA and Europe (Acreman et al., 2000). Some African floodplains still carry a large number of wild herbivores. Carrying capacities of 10,000 kg or more of wildlife biomass per square km are not uncommon in the non-flood season, e.g. in the Sudd floodplains along the Nile in Sudan (Marchand, 1987).
Relationships between flooding and wildlife performance tend to be more complex than for livestock, as it involves more species, each of them having a specific habitat requirement.
wildlife capacity→ wildlife habitat → flooding extent, duration and timing →EFR

Forestry

As with all natural floodplain systems, riverine forests are both flood-dependent and flood-tolerant. Most floodplains in temperate and tropical regions used to be forested, but have largely been converted into grasslands many centuries ago. In some countries floodplain forestry is still commercially viable, such as the hard- and softwood forests along parts of the Danube floodplain in Hungary (e.g. the Gemenc forest, see Marchand, Marteijn & Bakonyi, 1995).

While floodplain forests in semi-arid zones depend on minimum flooding frequencies and duration for groundwater recharge, and irregular major events create new sites for seedling establishment, flood-tolerance still appears to be a major determinant of forest distribution (Acreman et al., 2000). A typical example of flood-tolerance is that of mangrove forests that are able to withstand flooding of saline waters, but do require a certain input of freshwater in order to mitigate the salinity stress. The loss of mangrove forest as a result of reduced riverine discharge is well-documented for a large number of deltas. For instance in the Indus delta the mangrove ecosystem is being degraded, virtually mono-specific and comparatively stunted with losses of about 2% per year, largely as a result of the construction of Kotri barrage and the associated flood bunds which restricted the distribution of freshwater in the delta (Asianics Agro-Dev.International (Pvt) Ltd., 2000). In the largest mangrove area in the world, the Sunderbans, the reduced water inflow from the Gorai River, Bangladesh, is expected to cause serious negative effects on the mangrove vitality and species composition. Based on a ‘total wood volume - salinity’ relationship a reduction of wood volume from 43 cubic metres per ha to 17 cubic metres is expected for the primary impact zone when the current decline of Gorai discharge is continued (DHV-HASKONING Consortium and associates, 2001) . In arid and semi-arid areas where forest growth is limited by water availability to riverine areas, the value of these forests is clear and highly significant. It is the only source for timber and non-wood products (Acreman et al., 2000).
forest productivity → flooding extent, duration and salinity → EFR

Miscellaneous products

Rivers and associated (forested) floodplains, wetlands and deltas provide a multitude of products, most of which are collected by local people on a subsistence or semi-commercial way. Examples are non-wood ‘minor’ forest products, fruits, thatch material from plants, clay for bricks, gravel and sand, medicinal plants etc. The more diverse in species the ecosystems are the more important this function is. For example the riverine forests in the Tana River, Kenya provides food, construction material, medicines and more from many different plant species. At least 23 different species are used for providing medicines or remedies and 27 species are used for the making of arrows, baskets, beehives, mats, traps etc. (Acreman et al., 2000).

The relationship with flow requirements is complex as it involves many different species each with its own habitat requirement. Preservation of the entire ecosystem in its most natural structural diversity seems the best guarantee for maintenance of these functions.
ecosystem integrity→ flooding regime → EFR

4.4 Regulation functions

Purification capacity / water quality

Floodplains can remove nutrients (most importantly nitrogen and phosphorus) through the uptake and vigorous growth of its vegetation. Furthermore, river waters dilute and wash out pollutants which are then carried downstream and enter the sea. The freshwater volume can also impact the water quality through a change in residence time of the water, especially in estuaries. It has been recorded for the Hudson river estuary that reduced freshwater runoff can increase estuarine water residence time which may cause accelerated eutrophication. During the wet summers of the 1970s, water residence times were less than one day, but low freshwater runoff during the summers of 1995 and 1997 increased residence times to several days, resulting in 10-fold greater rates of phytoplankton production (Howarth et al., 2000). A more extended review of water quality and environmental flow is given in section 5.3.1.
downstream water quality → purification capacity floodplains and wetlands → flooding regime → EFR

Flood mitigation

The buffer action of wetlands (floodplains, marshes etc.) in a river catchment serves to reduce the often strong fluctuations in river discharge. It has thus been discovered that the peak discharges of rivers in Wisconsin (USA) are far higher in the case of river basins poor in wetlands than for those with abundant wetlands. Basins lacking wetlands have a discharge rate five times higher than those with 40% wetlands, for the same surface area (Noble & Wolff, 1984). Alongside this ‘sponge’ effect, this is of course also due to greater evaporation rates (Marchand & Toornstra, 1986). The relation with EFR’s is only instrumental in the sense that care should be taken that a flow release should not result in adverse flooding. It does not directly supports the flood mitigation capacity of a river basin.

Health

Rivers and associated floods are not always a blessing for mankind. Apart from disruptive mega-floods that may cause loss of lives and infrastructure, there are also health factors associated with river environments. Especially water related vector-borne diseases are important in this respect, such as malaria, Rift valley fever, Filariasis, Schistosomiasis and river blindness. Floodplains may also provide a permanent habitat for pests that threaten agricultural and livestock production (Acreman et al., 2000). On the other hand it is important to note that interventions in the natural hydraulic conditions for the benefit of irrigation and hydropower can seriously increase health problems as newly created freshwater habitats often serve as breeding sites for organisms that transmit parasitical diseases such as schistosomiasis and malaria. It is often the transition from temporary and flowing water bodies to permanent stagnant waters that may worsen the situation. For example in the Gounougou irrigation scheme along the Benue river in Cameroon it was found that man-made reservoirs harbour the largest numbers of intermediate hosts for schistosomiasis, which proved that this is to a large extent a man-made disease (Slootweg, 1994).

Controlling the health risks involves a truly interdisciplinary approach, in which not only the water management plays a role, but also the human behaviour as a determinant of its exposure to the vectors and the general health services are of equal importance. EFR's may be geared to improvement of the boundary conditions for a water management with due respect to health effects, such as minimising the risk of extreme and unexpected flooding and prevention of stagnant conditions.
health conditions → habitat conditions for vectors → flooding regime → EFR

Hydrological cycle

The regulation of the hydrological cycle is formed by a combination of water retention (by wetlands), groundwater recharge and groundwater discharge. It appears that the effect of wetlands in the upper watershed is realised only a few kilometres directly downstream. In contrast, large wetlands on the main stream have large effects on flood crests much further downstream. Water is spread over floodplains, where part of it recharges the groundwater and another part evapo(transpi)rates. Groundwater discharge maintains the flow in drier periods. (Dugan, 1990).
water retention; groundwater recharge → floodplain and wetland flooding → EFR

Moderation of salt water intrusion

Preventing salt water intrusion into the river system and groundwater is a well-known function of freshwater flow in deltas and river mouths. High salinities in lowland rivers may create problems for the intake of freshwater for domestic, industrial and agricultural uses. Due to the (natural) seasonality in river discharges the salt wedge is usually dynamic in nature and can extend up to many tens of kilometres upstream during the dry season and may be even absent during periods of high river discharge. For the conventional freshwater uses a minimum of salinity is often required. For maintaining brackish water environments, however (such as mangroves and lagoons), a certain extent of salinity intrusion is required.

Depending on the objectives, an EFR may either minimise intrusion or provide for an optimum salinity.
salinity concentrations → freshwater discharge → EFR

Estuarine and lagoon integrity

Freshwater inflow influences the integrity of estuaries and lagoons in a number of ways. Apart from the salinity effect (which is described in the previous paragraph), the volume of freshwater itself also has a hydraulic impact on the morphology. For instance many South African estuaries are temporarily closed during the dry season by a sand bar, which is pushed away during the high flow period.
morphology → freshwater discharge → EFR

4.5 Information functions

Gene pool, nature conservation

The ecological value of river and coastal ecosystems is often encapsulated with the concept of ecosystem integrity, which consists of two parts: functional integrity and structural integrity (Westra, 1994). An ecosystem's functional integrity is the maintenance of characteristic ecosystem processes, such as primary production, decomposition energy flows and nutrient cycling. Structural integrity encompasses the persistence of specific organisms and biotic communities in the ecosystem (Martin Fleming, DeAngelis & Wolff, 1995). For the maintenance of the information functions (such as the gene pool) the ultimate existence of these organisms (i.e. the structural integrity) is essential. However, these organisms can only survive if the functional integrity is high as well. Many EFR's are typically designed for the maintenance of ecosystem integrity. Although one might argue that all other river functions can best be maintained with maximum ecosystem integrity, we tend to limit this relation for the maintenance of habitat conditions for certain key valuable species.
gene pool, nature conservation → habitat conditions → EFR

4.6 Conclusion

The description of river functions and their relation with river flow clearly underlines the paramount role of the flow regime for the maintenance of these functions. All major processes that sustain these functions, such as flooding, moderation of salt water intrusion, sediment transport etc., are dependent on certain aspects of the discharge characteristics of the river. Evidently it is *not only* the maintenance of low flows that matter. For many functions other characteristics are important as well (e.g. mean annual flows, high flows, timing of the flood peak, its duration etc.). This is not to say that other factors are not important. Sediment input, water quality, temperature etc. also play their role and are determined by soil conditions, climatic factors and land use practices. These can be regarded as boundary conditions of the river (eco)system and river flow is the major factor that transforms these conditions to actual environmental parameters that can vary in time and place (see figure 4.3).

Also for riverine biotic communities there is evidence that they are driven by abiotic rather than biotic processes. Although biotic interactions do take place and have their influence on the species composition and abundance, it is now commonly assumed that flow regime is an overriding factor governing the nature and stability of communities in a river (King, Tharme & Villiers, 2000).

Having stated the importance of river flow, this does not automatically imply that EFRs can safeguard essential downstream functions and values. For instance, it does not influence the boundary conditions of a river, although it may mitigate adverse changes in it. EFRs are also generally not suited as a remedial measure for structural changes in the river, such as embankments that reduce flooding.

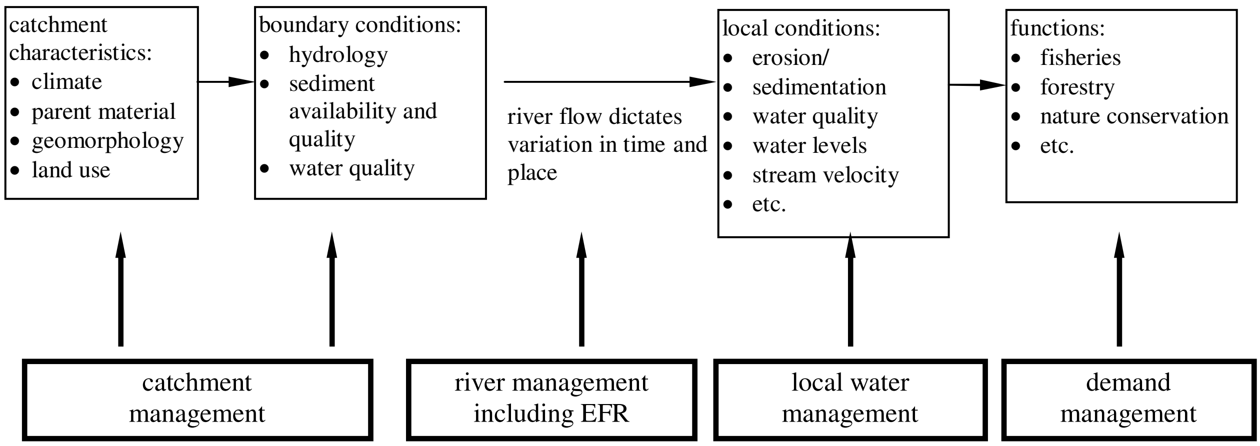

Figure 4.3: Hierarchy of scales in river processes with associated levels of management

5 Key environmental parameters

5.1 River flow dynamics

In the previous chapter an analysis is made of the river functions and their dependence on river flow. And it has been concluded that a substantial number of functions depend on river flow characteristics. It is clear that river flow is not uniform by nature, it varies between rivers systems, between tributaries and also in time. In order to make an explicit link between functions and river flow, we therefore have to analyse the river flow dynamics. Let us consider a hypothetical river with a distinct seasonal dry and wet season. Figure 5.1 presents a typical hydrograph of an average hydrological year. The key question is how to describe this behaviour and link the different components of the hydrograph to key processes that determine the function fulfilment or performance of a river. In other words, we are in search of key flow parameters.

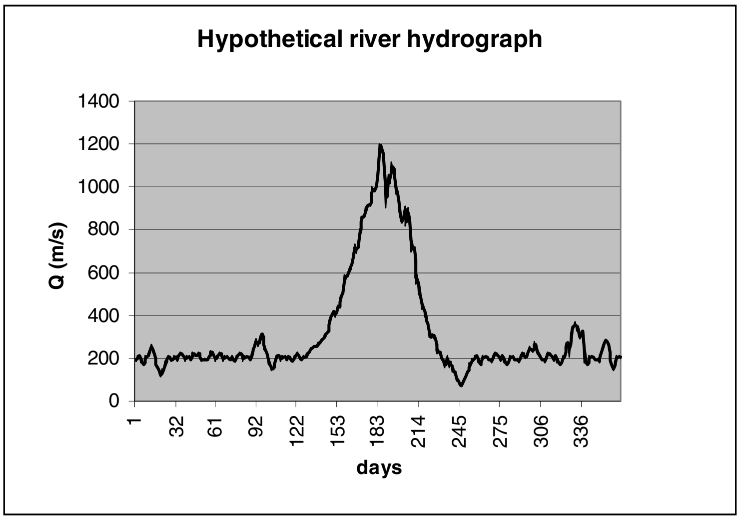

Figure 5.1: a hypothetical river hydrograph

Depending on the temporal resolution of discharge data we can describe flow dynamics in different levels of detail. In this example the discharge data are available on a daily interval, which is pictured in the above hydrograph. The most simple (and highest level of aggregation) is to calculate the Mean Annual Flow (MAF). The next, more detailed presentation is a graph showing the mean monthly flows (see figure 5.2). Typically this graph shows the seasonal differentiation in wet and dry months, but it does not provide the sub-seasonal variation within a month. Indeed, from the picture it can be seen that in the month of July the flood flow has a monthly average of nearly 1,000 m/s. However, from the hydrograph we can see that during this high flow month, peak discharges occur of 1,200 m/s. We can also see that there are actually two small peaks within the flood season.

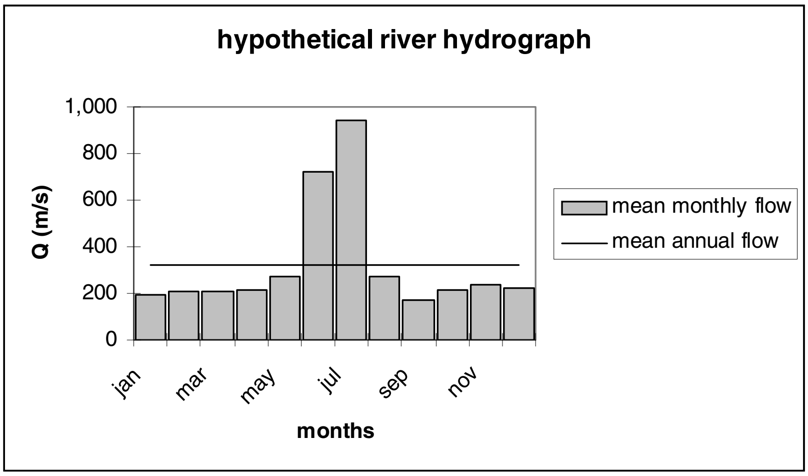

Figure 5.2 : mean monthly and mean annual flow, based on the hydrograph of fig. 5.1

Another typical representation of the flow characteristics is the use of the Flow Duration Curve. This curve shows the probability of exceedance of a certain flow (figure 5.3). Because in the example the database includes only discharge data of one year, the graph shows that the probability of exceedance above 1,200 m/s is zero. In reality, often datasets are available for a (large) number of years, which make it more likely that this peak discharge can occur.

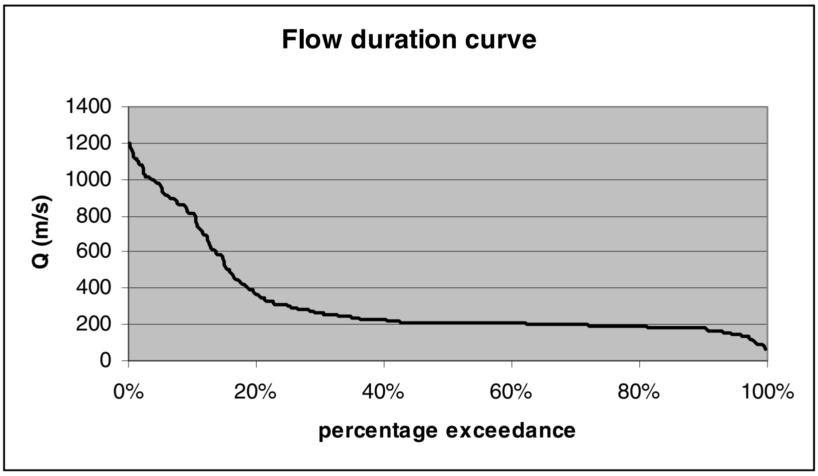

Figure 5.3. Flow duration curve based on the hydrograph of fig. 5.1

5.2 River flow classes

Based on daily (or even hourly) discharge data, a large number of parameters can be defined, of which the Mean Annual Flow is the most simple. In the literature one can find several attempts to describe the flow dynamics in terms of hydrologic parameters in relation to environmental flow assessments. One such example is that of Brizga *et al*. (2002), where the following flow indicator groups are discerned:

- total flow volumes
- annual variability
- seasonality
- zero flows

- low flows
- high flows

Table 5.1: Key flow indicators used by Brizga *et al*., 2002

flow indicator group	**key geomorphological and ecological functions**	**key flow statistics**	**definition**
total flow volumes	a measure of overall water availability in riverine systems and freshwater input to estuarine and marine areas	MAF (Mean Annual Flow)	total volume of flow in the simulation period divided by the number of years in the period
		Median Annual Flow	annual flow volume that is equalled or exceeded in 50% of water years in the simulation period
		Annual Proportional Flow Deviation (APFD)	a statistical measure of changes to both flow seasonality and volume
annual variability	a driver of geomorphological and ecological dynamics	Coefficient of Variation of Annual Flows (Cv)	a measure of annual variability, calculated by dividing the standard deviation of annual flow by the mean annual flow
		APFD	see above
Seasonality	• linked to lifecycles of riverine, estuarine and marine biota • synchronicity between main stream and tributary flows affect physical processes in the tributary	Flow Regime Class	a measure of flow retime seasonality, determined using Haines et al.'s (1988) methodology
		APFD	see above
		daily exceedance duration of monthly indicator flow (50% / 80% / 90% natural daily exceedance duration)	this performance measure is based on the daily exceedance duration of a monthly indicator flow, which is the natural 50% (or 80% or 90%) daily exceedance duration flow. The 50% daily exceedance flows is the flow that is equaled or exceeded on 50% of days during the simulation period for each month of the year
Zero flows	• de-watering of aquatic habitats • isolation of pools • no fluvial transport of organic matter or sediment dominance • dominance of marine influence in estuaries	Duration of Flows less than 1ML/d	the proportion of the total number of days in the simulation period (expressed as a percentage) when the daily flow is less than 1 ML
		number of spells of flow less than 1 ML/d greater than or equal to 1,3,6 and 9 months in length	the total number of periods of consecutive days of flow less than 1ML/d in the full simulation period greater than or equal 1, 3, 6 and 9 months in length
Low flows	• maintain ambient aquatic habitat in non-tidal reaches, and ambient hydrodynamic conditions in the estuaries • maintain connectivity between pools and between non-tidal reaches and estuaries	Daily exceedance for 10 (30) cm depth flow	the proportion of the total number of days in the simulation period (expressed as a percentage) when the daily flow exceeds a depth of 10 (30) cm above cease-to-flow
		number of spells of flow not exceeding 10 (30) cm depth grated than or equal to 1,3, 6 and 9 months in length	the total number of periods of consecutive days of flow not exceeding a depth of 10 (30) cm above cease-to-flow in the full simulation period greater than or equal 1, 3, 6 and 9 months in length
		daily exceedance of monthly indicator flow (50% or 80% or 90% natural daily exceedance duration)	see above
High flows	• channel maintenance • sediment transport • riparian zone and floodplain wetting • provision of wetland connectivity and replenishment • stimulus for breeding and dispersal • sediment and nutrient inputs to estuary and nearshore zone	1.5 year average recurrence interval (ARI) daily flow	the daily flow that has an annual probability of exceedance of 67%, that is every 1.5 years on average
		5 year ARI daily flow	the daily flow that has an annual probability of exceedance of 20%, that is every 5 years on average
		20 year ARI daily flow	the daily flow that has an annual probability of exceedance of 5%, that is every 20 years on average
		Mean Wet Season Flow	the total flow in the wet season months of in the simulation period, divided by the number of years in the simulation period

Source: Brizga *et al*. (2002)

In table 5.1 an overview is given of the key flow indicators used by Brizga *et al.* (2002), their geomorphological and ecological functions and their way of calculation. Another example from the literature is the Range of Variability approach (Richter *et al*., 1997) which uses 31 indicators of hydrological alteration, grouped into the following classes:

- Group 1: magnitude of monthly water conditions
- Group 2: magnitude and duration of annual extreme water conditions
- Group 3: timing of annual extreme water conditions
- Group 4: frequency and duration of high/low pulses
- Group 5: rate/frequency of water condition changes

Table 5.2 provides the full range of hydrologic parameters.

Table 5.2. Summary of hydrologic parameters used in the Indicators of Hydrologic Alteration and their characteristics

IHA Statistics Group	Regime Characteristics	Hydrologic Parameters
Group 1: Magnitude of Monthly Water Conditions	Magnitude Timing	Mean value for each calendar month
Group 2: Magnitude and Duration of Annual Extreme Water Conditions	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means
Group 3: Timing of Annual Extreme Water Conditions	Timing	Julian data of each annual 1-day maximum Julian data of each annual 1-day minimum
Group 4: Frequency and Duration of High/Low Pulses	Frequency Duration	# of high pulses each year # of low pulses each year mean duration of high pulses within each year (days) mean duration of low pulses within each year (days)
Group 5: Rate/Frequency of Water Condition Changes	Rates of Change Frequency	means of all positive differences betweeen consecutive daily values means of all negative differences betweeen consecutive daily values # of rises # of falls

Source: Richter *et al*. (1997)

Comparing the two approaches it becomes clear that there are overlaps as well as differences between the two. The method of Brizga *et al*. has a fairly extended list of parameters describing the extremes (zero, low and high flows) in different ways and also includes different parameters for total flow volumes. Lacking are parameters that indicate timing of extreme water conditions and rates of changes, as are included in the RVA approach. On the other hand, the RVA approach does not take annual flows explicitly into account and does not explicitly relate the parameters to key geomorphological and ecological functions. Using the best of two worlds, a proposed framework for defining key flow parameters in four major classes is described (see table 5.3).

The rationale behind this division into four river regime classes is the fact that river functions put different types of demands to the discharge regime. Some functions are only dependent on total (annual) flows, while others depend on seasonal differences in flow, yet others are determined on extreme water conditions and finally some are influenced by the smoothness (i.e. rate of change) of the discharge.

Typically river hydrographs are made for one year, and the regime classes can accurately describe this. Of course not a single year is hydrologically identical, as there is interannual variability. Hence, the parameters that are used to describe the different classes can or should have some kind of probability (see for instance the flood duration curve). Especially for the extreme events there is a large difference between the temporal resolution of the event itself (usually on a scale of days or weeks) and the frequency of occurrence (once in 10 years for instance). Parameters that describe these extreme events are therefore always a combination of magnitude and frequency of occurrence.

Table 5.3. Proposed classification of hydrologic parameters according to regime characteristic classes

regime characteristics class	description	parameter class	example parameter
I. annual flow variability	a measure of overall water availability in riverine systems and freshwater input to estuarine and marine areas	magnitude of annual flow	• MAF • median annual flow
II. seasonality	a measure of distinct seasonal differences in discharge, usually related to climatic factors in the catchment	magnitude and timing of mean monthly flows	• mean flow value of each calendar month • Flow Regime Class (cf. Haines et al., 1988)
III. extreme water conditions	a measure of maximum and minimum discharges with different probabilities	magnitude, timing and duration of extreme flows	• value and Julian date of annual 1-day maximum • daily exceedance for 10 cm depth flow
IV. smoothness	a measure of reversals in the rise and fall of discharges	frequency and duration of pulses and rates of change	• # high pulses each year • # rises and falls

Through this model all relevant processes are covered that determine functions with a typical time horizon of decision making on e.g. days and seasons (for instance for the livelihood of local people) up to several years and decades (for river managers). Evidence of complete coverage can be provided through the following diagram. When we plot all possibilities of a flow event in terms of its duration and frequency it can be shown that each of the flow classes cover all relevant possibilities (see figure 5.4). Flow events with a duration of days or weeks can occur either very often and can change relatively fast, which are then characterised by the smoothness of the hydrograph; or are rather unusual, which we then call extreme events. Mean monthly flow variation typically shows a distinct seasonal change in many rivers (hence with a high probability of once in every year), which is characterised by the seasonality of the river. Annual flows change from year to year and are described by the annual variability. Sometimes a typical sequence of unusually dry or wet years can be distinguished, that can be described by a variation in the decadal trend. This decadal variability has not been given a separate category, as this phenomenon can easily be included in the annual variability.

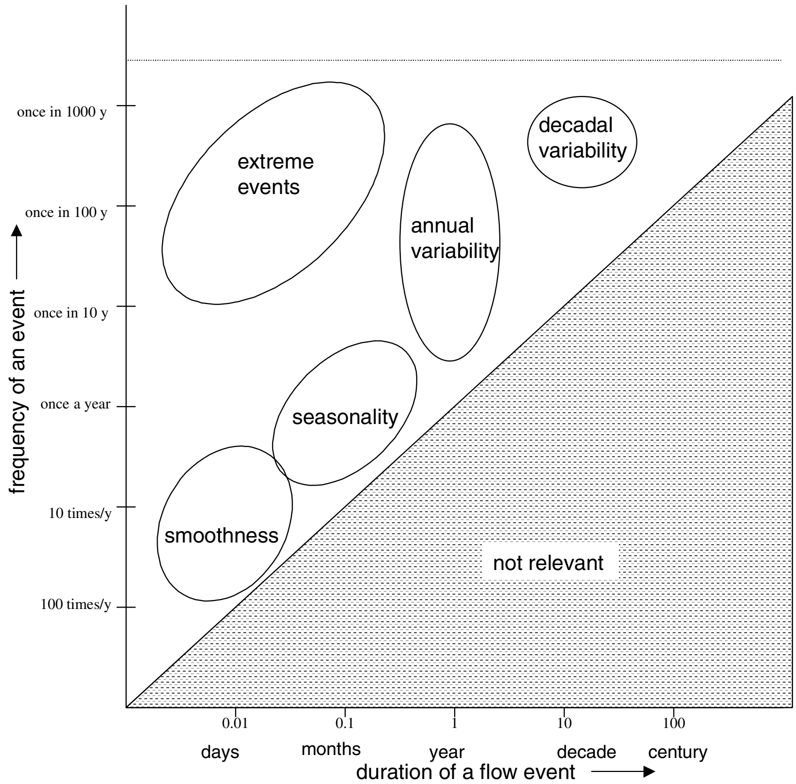

Figure 5.4: diagram showing the relation between the duration and frequency of a flow event.

Based on the above model description it is postulated that the entire scope of river dynamics can be described through this division into four (and *only* four) classes. Because not all river functions are equally dependent on the river characteristics, it is important to identify the relationship between flow class and river function. Thus a quick reference can be made with respect to the relevancy of each flow class in case an environmental flow requirement is to be assessed. Table 5.4 provides a listing of the major river functions, their performance indicator and their most relevant (key) environmental parameters and flow class.

Table 5.4: Relating river functions with key hydrological parameters and flow dynamics classes

Function	**performance indicator**	**key environmental parameters**	**key flow class**
1. navigation and transport	number of days per year below a certain water depth	water depth (Q-h relationship); long term morphological changes due to large scouring floods that occur less often than once a year	III. extreme events
2. riverbank occupation	length and severity of eroding banks; annual rate of surface area eroded/accreted	morphological dynamics due to large scouring floods that occur once a year or less	III. extreme events IV. smoothness
3. coastline stabilisation and delta formation	length and severity of eroding coastline; annual rate of surface area eroded/accreted	sediment transport	III. extreme events
4. drinking/ industrial water	number of days per year below a certain water depth related to intake structures; water quality (see 14)	water depth (Q-h relationship)	III. extreme events
5. water for washing/ bathing	number of days per year with zero flows		III. extreme events

Function	performance indicator	key environmental parameters	key flow class
6. hydro-power generation	number of days on which power generation falls below standard	recurrent years of low flow that reduce reservoir functioning	I. annual flow variability
7. recession agriculture	cropping area and crop yield per ha	soil moisture as function of sufficient and timely flooding	II. seasonality
8. river fisheries	fishing yield	fish recruitment as function of flooding extent and quality of flood	II. seasonality III. extreme events IV. smoothness
9. coastal fisheries	fishing yield	lagoons: salinity and connectivity marine: Range of Freshwater Influence (ROFI)	I. annual flow var. II. seasonality III. extreme events
10. livestock herding	livestock carrying capacity	grassland productivity as function of flooding extent and timing	II. seasonality
11. hunting	wildlife carrying capacity	habitat for wildlife as function of floods and flow variability	II. seasonality IV. smoothness
12. forestry	extractable annual wood volume and non-wood products	freshwater forests: flooding frequency, duration and extent mangroves: salinity	II. seasonality III. extreme events
13. miscellaneous products	biodiversity	diverse habitats as function of low flows, floods and flow variability	II. seasonality III. extreme events IV. smoothness
14. purification capacity / water quality	WQ standards	- dilution and flushing - quality of water from reservoir - purification capacity of floodplains and wetlands as function of vegetation growth - suspended sediment transport	all classes
15. flood mitigation	exceedance probability of design water level	water depth (Q-h relationship)	III. extreme events
16. health	prevalence of diseases flooding casualties	habitat conditions for vector organisms extreme and unexpected flooding	III. extreme events IV. smoothness
17. Moderation of salt water intrusion	upstream extent of the salt wedge	hydraulic forcing and mixing of fresh and saline water	II. seasonality
18. hydrological cycle	groundwater availability over the year	water retention and groundwater recharge	I. annual flow var. II. seasonality
19. estuarine and lagoon integrity	maintenance of estuarine and lagoon connectivity with the sea	morphological dynamics due to large scouring floods that occur once a year or less	II. seasonality III. extreme events
20. gene pool	biodiversity	diverse habitats as function of low flows, floods and flow variability	all classes
21. tourism & recreation	landscape amenity biodiversity (see nature conservation) sailing opportunities (see navigation) sports fishing (see fishery)	relating to many other functions such as nature conservation, fishery, forestry, hunting, water quality, health etc.	see other related functions
22. existence value (conservation)	biodiversity	diverse habitats as function of low flows, floods and flow variability	all classes

Table 5.4 (Cont.)

For instance for navigation and transport the number of days on which no transport is possible for ships of a certain draught is an important performance indicator. To be able to calculate this indicator one has to know the probability of a ‘design’ flow (defined as a flow required for a certain water depth) below which navigation is not possible. The relation between flow and water depth can be attained from Q-h relationship, whereas the key regime class is extreme water conditions. For hydro-power generation a similar type of performance indicator can be used, namely the number of days on which no power generation can be provided up to the desired standard. In this case, however, not the extreme water conditions are important, as these can be buffered by the reservoir. Instead the variability in annual water volumes is more important, as a number of consecutive years of low annual flow reduces the performance of the reservoir. Of course this depends on the relation between reservoir volume and average mean annual flow.

The example of floodplain fishing shows perhaps the most complex relation between a function and river discharge. According to Welcomme (2001) the performance of the fishery is dependent on the quality of the flood, which is defined by:

- timing of the flood
- amplitude of the flood
- the flood duration
- the rapidity of change
- the smoothness
- the drawdown period (the amount of water remaining in the system at low water)

In figure 5.5 these characteristics are depicted for a typical flood curve. The required flow characteristics fall under the categories seasonality, extreme events and smoothness.

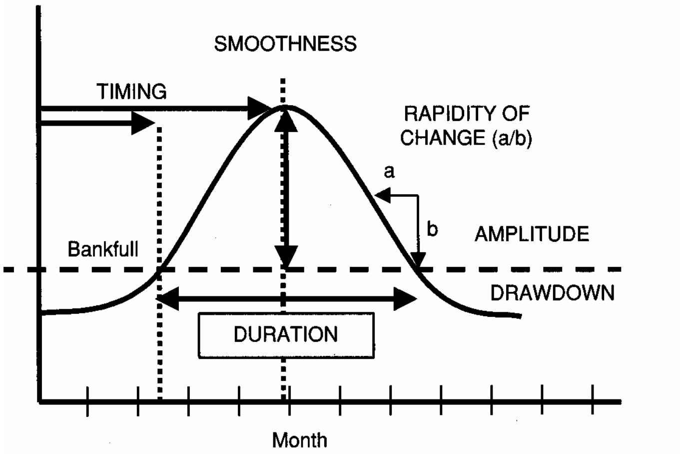

Figure 3.5. Fisheries characteristics of a flood curve (Source: Welcomme, 2001)

5.3 Water quality and flow

The functioning of a river system not only depends on the flow characteristics, but also on concentrations, amounts and characteristics of the materials transported by the river, like sediments and dissolved substances. To be of any use to the (downstream) environment the water, for many functions such as drinking water, irrigation and fisheries, needs a certain basic quality. There is a separate report on the most important water quality aspects that have a linkage with the main ENFRAIM objective (Vis et al., 2003). Therefore in this report only the main findings of research on the water quality are included in the next sections. In section 5.3.1 pollution aspects of rivers in relation to environmental flows are discussed. Section 5.3.2 deals with the sediment budget and suspended solids in rivers, whereas in section 5.3.3 the salinity related processes and phenomena are discussed.

5.3.1 Pollution

The complexity of the chemical processes that influence water quality makes it difficult to give general guidelines for taking into account water quality in the setting of environmental flows. There are a vast number of substances, each with their own behaviour and degradability and each of them react differently under different geographical conditions, seasonal variations etc. Very detailed modelling approaches have been designed throughout the world to analyse and to try to understand the relation between specific chemical substances and the overall quality of water in river catchments. Each of these has specific features or level of detail depending on the objectives of the study. The few EFR methods that do take into account water quality use the environmental flow to dilute the pollution ('flushing'). However, many would not consider this as a true EFR, partly because there may be no overriding concern about the functioning of the whole riverine ecosystem, and partly because it is felt by many that water pollution issues should be addressed at the source (King, Tharme, & Brown 1999). Indeed, it is true that practices in the entire watershed itself are often more important in causing water pollution downstream than changes in the river discharge itself. On the other hand, it is unwise not to account at all for water quality effects in setting EFR's.

Generally speaking there are five different effects on the downstream water quality to be considered which may play a role in abstractions and impoundments of river waters and thus for an EFR as a mitigating measure:

1. Effect on downstream dilution and residence time
2. Release of anoxic waters (from a reservoir)
3. Reservoir as "treatment plant"
4. Effect on hydrology and water quality of adjacent surface waters
5. Change of transport of particulates (incl. N, P, Si,…)

Each of these mechanisms is discussed in the report by Vis et al. (2003).

5.3.2 Sediment and suspended matter

The presence of suspended solids and sediment in rivers is an important physical characteristic. Such sediment can have both a direct effect at the aquatic life (e.g. fish!) through damage to organisms and their habitat and an indirect effect through its influence on turbidity and light penetration. High concentrations of suspended sediments make the water less suitable for the production of drinking water, for irrigation purposes as well as for industrial use. Furthermore, the sediment budget is an important parameter for the morphological development of rivers. Vis et al. (2003) distinguish a total of 35 processes, phenomena and human interference that influence the sediment condition of a river, divided into (a) sources of sediment, (b) transport mechanisms, (c) effects on water quality and river morphology, (d) impacts on biota and (e) mitigating measures. Environmental flows can to a certain extent be used to influence some of these processes, such as flushing of sediments, ensuring sediment deposition through flooding etc. One aspect that is gaining importance is the use of EFR's to preserve the long term river morphology by assuring high flows of relatively low frequency. As the changes of river morphology are due to the erosion, transport and settling of sediment, the largest amounts of sediment are transported by the river during high-flows and not at average or low-flows conditions. High discharges, originating from extreme rain-fall events somewhere in the catchment with a return period of more than one year, are generally thought to represent the 'formative condition' for the river morphology (Peart (1995), Schouten et al. (2000)). However, the discussion on formative conditions has not been resolved yet, and the importance of low frequency - high magnitude events should not be overestimated as is indicated by Wolman & Miller (1960): “Observations suggest that the effectiveness of processes which control many land forms depends upon their distribution in time as well as their magnitude. It cannot be assumed that, simply because of their magnitude, the rare or infrequent events must be the most significant. Analyses of the transport of sediment by various media indicate that a large portion of the "work" is performed by events of moderate magnitude which recur relatively frequently rather than by rare events of unusual magnitude".

5.3.3 Salinity

To determine the optimum salinity one has to keep in mind that estuaries are highly dynamic systems and are under the influence of both river flow and tidal movements. Generally, estuaries can be classified according to the level of stratification/mixing, i.e. highly stratified, partly mixed or well mixed. Within this general classification, seasonal changes in river flow can temporarily change the ‘normal’ condition of an estuary. Usually the estuarine ecosystems and their species are adapted to this highly dynamic environment as long as these seasonal variations remain within the average natural dynamics. Upstream water diversions can permanently change this pattern with significant consequences for the estuarine ecosystem (for more information see Vis et al., 2003).

5.4 Conclusion

EFR’s should not a priori be limited to a specific aspect of the river regime, such as a minimum or guaranteed low flow. Instead, the full range of the river dynamic should be taken in consideration, which can be described in four classes: annual flow variability, seasonality, extreme events and smoothness. For each of the classes parameters can be used, many of which are already described in the literature. Interannual variability is equally important and should be represented in the parameters in terms of a probability. Linking these flow parameters with ecosystem integrity and sustainability is essential when assessing an environmental flow for a river. Besides the direct influence of flow on ecosystems also the indirect mechanisms should be taken into account, through a causal chain involving water quality, sediments and (in the coastal domain) salinity parameters. In chapter 7 the ecotope concept is described as an approach to integrate these parameters in a spatial context.

6 Human well-being and environmental flows

6.1 Introduction

Based on the four main categories of river functions (see Chapter 4) a wide range of water uses and river values can be distinguished. Comprehensive river management has the task to ensure that each of the *relevant* environmental functions is sustained in a balanced way. That implies taking into account the interests of stakeholders which operate at different levels of the society, including urban residents, industries, hydro-electricity companies, the agricultural lobby, environmental groups, tourists and last but not least the local communities living along the river. An environmental flow requirement is often seen as the vehicle through which the interests of hitherto neglected 'parties', especially nature itself, is expressed. But it is increasingly recognised that environmental flows can also express the demands of local communities for their share of river water, either used directly or through the services provided by the riverine and coastal ecosystems. Recent studies of the economic importance of formal and informal activities in local economies demonstrate this point (King et al., 1998; Scudder, 2002). The importance of natural resources in sustaining peoples' livelihoods and well-being is getting more attention in several EFR methods, especially the holistic ones, such as the Building Block Method. But how these needs should be addressed remains to be dealt with and is far from trivial. One aspect is to gauge the specific use of river functions for the local livelihood in order to translate them into an environmental flow requirement. Another is how these interests should be taken into account in a wider river basin context in which the local communities have only a limited voice. The first question is addressed in the following section, based on preliminary findings of a field study in Bangladesh, while the latter will be dealt with in a section that is based on field work in Kerala, India.

6.2 Assessing the relationship between river functions and the well-being of people

6.2.1 well-being of people

Water is essential for the life of people. River ecosystems have various functions for the people living alongside these rivers, e.g. for drinking, washing, bathing, but also for fish and the collection of other food, of construction materials, or for navigation. People in rural areas may depend on these functions to various degrees, e.g. for their entire income, for their own food supply or for drinking water only. Changes in the flow regime affecting the availability or presence of river ecosystem functions are therefore likely to have an impact on the lives of these people. To assess the relations between river flow and people there are a number of methodological hurdles to overcome. The following (interrelated) questions need to be answered:

1. how can the differentiation in use between groups of people be effectively addressed?
2. how can the use of river flow be related to (indicators of) livelihood?

3. how can information on the previous questions be obtained from the field?

Ad. 1 Differentiation

The socio-economic value of a good or service depends on the way it contributes to human welfare (De Groot, 1992). Different groups of people may have different understandings about what they consider human welfare, and may also use different functions to contribute to their own welfare. Consequently, the first step must be to identify *different groups of people* living along a river. Groups of people can be distinguished by, for example, main income source, geographical location, household income or gender. Each of these groups have a different relation with the river. For instance, fishing communities traditionally depend for their income directly on the river ecosystem, whereas for other communities the fish from the river may be only a part of their diet. Communities upstream are usually less impacted by river alterations than those living at the downstream end. Within communities there are often large differences between household incomes, usually reflecting a difference in susceptibility to changes in the local (river) environment. And finally, within households there is the gender difference that influences the perceived importance of river functioning between men and women. If, for example, women are responsible for obtaining drinking water and have an own income from home-garden cultivation, and men are mainly responsible for field cultivation, a change in groundwater recharge due to reduced flooding is likely to affect women more than men.

Figure 6.1: river transport on the Teesta River, Bangladesh (photo by K.S. Meijer).

Ad. 2. Livelihood and well-being

The relationship between well-being and the functions of the river-ecosystem is not unambiguous. First of all, there is no clear definition of what well-being comprises. A number of parameters, such as income, food, health, will constitute a certain sense of well-being. One aspect in assessing the importance of a certain river-ecosystem function for a person’s well-being is the availability of alternatives. For example, if river water is used for bathing, but groundwater pumps are available as well, a reduced river flow may have a different effects on a person's well-being than if river water was the only available fresh water source. If different sources are available, it may be interesting to understand people's preferences. For example, some people may prefer river water for bathing because the river water is close to their homes, while others prefer water from a pond, because they consider the river water to be dirty. Distinguishing between the different available and preferred sources is necessary, since they will result in different requirements to the flow regime, in terms of flow regime characteristics as well as in terms of the urge of the requirement.

The livelihood concept is considered a useful approach to determine the dependence of people on the river for their well-being. Livelihood is considered to be the mix of human, social, financial, natural, and physical capital, which they can use following certain livelihood strategies (e.g. farming or fishing) to pursue livelihood outcomes (e.g. more income, better health)(DFID, 2000, in Acreman et al., 2000). A changed river flow with consequences for the services provided will result in a different livelihood strategy (i.e. replacing lost sources with alternatives), which may be less favourable from a micro-economic point of view. The way to deal with these transitions is therefore to look at trade-offs between goods and services provided by the river and by other sources *within* a livelihood context. For instance, it may be well possible to replace a river function (e.g. free water for drinking purposes) with an alternative (such as piped drinking water for which one has to pay), but this may have a different impact on groups of people due to their different livelihood c.q. economic status.

Ad. 3. Information gathering

In order to provide information on the stakeholders' perceptions towards river functions, the same methods can be used as for any other environmental or rural development issue that focuses on people's well-being. For instance, the Participatory Rural Appraisal (PRA) technique (Chambers, 1983) is a well-known example that can be used in EFR's (see King et al., 1998). A typical problem encountered in gathering information from the field is the fact that the perception to the issue of the researcher and stakeholder often varies considerably. Local people do not use words like *function* or *discharge* and they may be unaware of the relationship between e.g. groundwater level and river flow. Nevertheless they often have a large body of indigenous knowledge based on experience over many years. It is the challenge for the researcher to tap this knowledge and put the appropriate linkages into place that make up the dependency of livelihood to river flow. The function approach described in Chapter 4 may be of guidance to this effort, but the researcher should always have an open mind to the local situation, which may (and often will) change the initial set of relevant functions for that specific river setting.

A clear example of the adaptation of the originally set up of a list of river functions after executing field work is the situation of the Teesta River in Bangladesh. A pilot case study was conducted by Meijer (2003) near Kaunia along the Teesta River in May 2002. A combination of methods (observation, group discussion, workshops) was applied to assess what products and services the people along the river use and in what way these functions contribute to their well-being. The investigation among the stakeholders revealed that the ecosystem provides many products and services, which were not identified beforehand. For instance, the use of water hyacinth was mentioned explicitly as a means of cheap fertiliser, and also the negative effect of flooding was emphasised, something which was not considered in the initial list of river functions.

Identifying both the stakeholders and the functions of the river will probably be an iterative process. Authorities may mention the main functions the river ecosystem has in their perception, which leads to certain stakeholders. Interaction with stakeholders may reveal other functions, which may lead to different stakeholders, who in turn reveal even other functions, etc.

In conclusion one can state that although the involvement of local stakeholders in the process of environmental flow assessment is not easy, time consuming and requires full commitment of those involved, it is essentially not different compared to other fields of participatory planning, such as rural development programmes. Up till now the socio-economic importance of natural river flows have been seriously overlooked by planners, practitioners and academics. But similarly to the problem of resettlement of people in the case of dam construction, this aspect of river development requires ample attention, not in the least because of the often many more people involved than in the resettlement alone (Scudder, 2003).

6.3 Institutional arrangements for integrated river and coastal management

The setting of an environmental flow requirement is a typical example of a management decision at a supra-local and sometimes supra-regional level that requires an integrated approach. Integration implies here: multi-actor, multi- level, multi-sector as well as including multiple physical domains (i.e. hydrology, geomorphology and ecology). Hence, it is not something that can be dealt with and managed at a local level by local people themselves. Therefore, institutions are required to aid decision making and management. The functions of institutions are two-fold (Bandaragoda, 2000):

- constraining socially undesirable behaviour by individuals and groups in natural resource use (here: water use) on the one hand, for example by resource allocation rules; and
- reducing uncertainty of human actions, and thereby having a stabilising effect on society, on the other hand, for example by centrally imposed or externally mandated institutions.

Although institutions are a necessary condition for actually implementing EFR's, sometimes they are also part of the problem. Because of the great distance that often exists between a management institution on a regional/national or catchment scale level and the local communities, the needs and interests of the latter are often not effectively accounted for on the management level. This is a common phenomenon in many countries, not only with respect to water management, but for many other issues as well, including rural development. Therefore, a tendency exists to encourage decentralised governance systems that increase the empowerment of local communities. Local governments are perceived as more responsive to local needs and concerns, and as having the flexibility to network and develop partnerships with other public sustainability goals by transferring environmental responsibilities to local people. However, the practice of decentralisation shows that there are several unforeseen pitfalls that undermine the above stated assumptions about decentralisation in regard to natural resource management goals. Case-studies from different continents demonstrate that political or administrative boundaries often do not coincide with ecologically determined boundaries for natural resource management. Also, decentralisation seldom transfers power in an all-in-one package of responsibility. Another pitfall is the assumption that local hands are prepared for taking up more and new responsibilities while this depends on a combination of factors largely beyond control of the reformers themselves. Prior established relational patterns do not just disappear with decentralisation nor does decentralisation make socio-economic relations more equitable. In fact, it may even empower the local elite compared to less privileged parts of the community. The prevailing political climate considerably influences the chances to establish successful decentralised management institutions and practices and can disrupt the continuity of decentralised management efforts. These observations suggest that a strong institution is required to mediate the relationships involved in a decentralised management structure (Wyckoff-Baird, 2000).

In a case-study, conducted as part of the DC ENFRAIM project in Kerala, India (see box 3), the problems of decentralised resource management as well as institutional ineffectiveness are clearly highlighted (Gangaram Panday, 2003). The Vembanad lake is a typical example of an estuary where the natural salinity gradients have been modified through a barrier, splitting the lake into a more or less freshwater part and a marine dominated environment. This man-made intervention created an abrupt disruption of the physical and biological continuity of the lake and the destructive consequences hereof have thus not stayed away. Agriculture and fisheries have been two of the most important production functions of this wetland system. However, a series of state interventions of which the barrier is the largest, have focused on the development of rice cultivation while neglecting other functions of the system at large.

Regulators in the barrier could allow for an environmental flow in either direction (i.e. freshwater going seaward during the monsoon season and sea water flowing into the lake during the dry season), but this would require at least:

1. a technical upgrade of the sluices, as currently the majority is non-functioning due to lack of maintenance
2. an agreement between the different stakeholders, especially the agriculturists and fishermen on the ideal environmental condition of the lake (i.e. the objective of EFR)
3. an environmental flow assessment, taking into account all physical and ecological processes that provide a range of lake services.

The current decentralised local-self management system does not seem to address the environmental situation of Vembanad lake explicitly. However, it could provide a major vehicle through which the interests of the different local communities can be given a voice. Apparently it is not the lack of a managing authority of the barrier itself, that is the problem, but the lack of interest or inertia of the responsible government agencies to address the true problems of at least part of the population. One aspect that also needs to be considered in this respect is the observed lack of sufficient information and skills at the local level with regard to these environmental issues. Several local people have voiced the willingness to address these issues, but they feel that they are missing essential information. As Kerala has a comparatively high level of education (literacy rate is among the highest in India) and it has several universities, the implementation of an environmental flow assessment, based on a function approach as described in chapter 4 in connection with a stakeholders assessment illustrated in section 6.2 seems to be feasible as well as justified.

Box 3: the example of Vembanad lake, Kerala (India)

India's south-western state of Kerala is a narrow strip of land between the Arabian/ Lakshadweep Sea and the Western Ghats, a chain of mountains. Kerala is well-known for its 30 interconnected brackish water estuaries and lakes covering 2428 km^2, more or less parallel to the state's 590-km coast. The Vembanad lake is the largest backwater and spreads out over 365 km^2. On the east, rivers discharge freshwater into the lake while in the west it is connected to the Arabian Sea at the Cochin barmouth.

In 1976, a salinity barrier, located halfway of the lake was constructed to prevent upstream intrusion of saline water during the dry season. Originally the barrier was planned to be closed from mid-December to mid-March, allowing the upper stretch of the Vembanad Lake to become saline during the pre-monsoon period. However, until 1991, the barrier was closed for about 6 months (December to May), and the water upstream of the barrier remained practically fresh throughout the year. The number of fish species is believed to have decreased by about half. This decline is caused by a complex combination of factors of which the drastic change in salinity is the most important one, but probably the deteriorating water quality, the type of nets used, the increase of fishing intensity and land reclamation also play a role.

The construction and subsequent operation of the salinity barrier was meant to augment the amount of fresh water during the dry season, in order to enable two rice crops per year. Revised operation rules were studied in late 1980's, in order to reconcile both the agricultural and fishery requirements (Van Maaren, 1989). However, the problems regarding the operation of the barrage still have not been resolved. In a recent study by Gangaram Panday (2003) the following observations were made:
The barrage was constructed with only about two-third of the originally designed number of gates, closing one-third of the lake's width permanently without considering the effects hereof.
Operation of the barrage has been dependent on politics and lobbying by vested interests, especially the more dominant agricultural lobby, rather than scientific or resource management considerations.
Bad maintenance had led to a number of defunct gates that also hamper proper operation of the barrage.
Local fishermen continue to express their worries and problems regarding fisheries in the Vembanad Lake. Since they have had little to no success, they sabotage proper closure of the gates.
Several committees have studied the Lake's problems and given recommendations ranging from complete removal of the barrage to changed operational rules. However, implementation of recommendations has proven hard to accomplish with politics and strong lobbyists involved.
Overall, bad construction, bad operation and bad maintenance of the barrage have resulted in the situation as it exists today.

Observations regarding decentralisation in Kerala are:
The in 1997 established Local Self-Governance system (Panchayat Raj) has until now emphasised on economic, infrastructure and social welfare projects while environmental issues are almost not addressed.
Natural resources management has not in effect been decentralised since specific legal and administrative reforms are not realised, there is no clear functional division of tasks, and the local bodies lack the capacity to take this up on their own.
Since the state government's switch in 2001, local self-governance has received no priority; further development of decentralised management will probably have to wait for the next left government.

This example clearly demonstrates how a one-sided approach towards development can lead to serious destruction of a natural ecosystem, and why consideration of all functions as could be realised in an EFR is of vital importance.

The situation described for Kerala is not unique. Even in a country as South Africa, with the most modern water law in the world giving ample attention to environmental flows and stakeholder involvement, the institutional implementation of an EFR is not without problems. Lack of human resources, sufficiently skilled in the topic of EFR, within the relevant government departments was identified as one of the main constraints for the actual implementation of EFR's in South Africa (Louw et al., 2002). And although the determination of the 'Reserve' (i.e. EFR) in South Africa requires the input from stakeholders, their involvement has up till now been modest, as stakeholder processes are expensive and contentious (Louw et al., 2002). Also the World Bank acknowledges the problems of institutions, which currently seems to be the rule rather than the exception as it states that ‘Comprehensive water management is inherently difficult and institutional reforms to achieve it are time consuming and often take more than a decade to mature’ (Hirji & Panella, 2002).

7 Ecotopes as an integrating concept

7.1 Introduction

In chapter 5 attention was given to the temporal dynamics of the river flow, the entire scope of which is relevant for sustaining the range of functions rivers may provide. This leaves the spatial dynamics and patterns yet to be defined. Many river classifications have been made, for many different purposes (for an overview reference is made to Penning, 2001). For the purpose of environmental flow assessments, different approaches and methods for dealing with the spatial variability can be found, although compared to the temporal flow dynamics, the number of methods explicitly dealing with spatial analysis is strikingly limited.

Usually an EFR is assessed for one or several river sections, each of them represented by one or more ‘study sites’. For instance, in the Building Block Method four sites are considered usually sufficient to represent a river length of 100-200 km (King et al., 2000). Data collection for these sites is usually done through cross-sections indicating the local hydraulic situation, substratum and vegetation cover. Similarly, the Benchmark method uses a spatial reference framework, implying the division of the river in the study area into reaches characterised by a relatively homogenous flow regime, geomorphology, water resource development impacts and other human impacts (Brizga et al, 2002). Habitat methods, such as IFIM, are specifically geared towards obtaining information on the area of total suitable habitat, e.g. through multiplication of the habitat area per mile of stream with the number of miles of usable stream (Stalnaker et al., 1995). Although attention is given to the spatial heterogeneity of rivers (using river classifications such as from Frissell et al., 1986) and improvements have been made for handling the biological data collection at a scale that is relevant to management (i.e. to larger units than the micro-habitat level) (Parasiewicz, 2001), these methods still contain two major limitations: 1) they are usually limited to the aquatic river channel environment, leaving large parts of the river corridor such as floodplains unattended, and 2) they tend to focus on habitats for a limited set of species, usually fish.

A recent attempt to overcome the above limitations is the geomorphological framework for river characterisation and habitat assessment (Thomson *et al*., 2001), forming a logical extension of the River Styles framework that characterises river form and behaviour at four inter-related scales: catchments, landscape units, River Styles (reaches) and geomorphic units. These geomorphic units include both instream and floodplain landforms (pools, bars, levees, backswamps etc.) and thus provide a sound basis for determining habitat availability for both aquatic and terrestrial flora and fauna with the additional advantage that no *a priori* selection of species is required.

This state-of-the-art with respect to the spatial scale of EFR methods clearly shows that there is a need to further explore new ways of dealing with this issue. We have chosen for the elaboration of the ecotope concept as part of a flow assessment and will show the applicability of this approach in the case-study of the Surma-Kushyara rivers in Bangladesh.

Linkages will be made with the previously described function approach as well as the river regime classes.

7.2 Description of ecosystem characteristics through ecotopes

7.2.1 Definition

To evaluate the impacts of a changed flow regime on the production and information functions an approach is used in which the concept of the ecotope plays a key role. The term ecotope was first used by Tansley in 1939. Troll (1968; 1970 cited in Klijn, 1997) was the first to make the ecotope concept operational. Ecotopes are generally regarded as the smallest ecological land units that are relevant in landscape ecology. They are defined as:
ecological land units that are homogeneous with regard to the vegetation structure, succession stage and the predominant abiotic environmental conditions that determine the species composition of the biotic community (Klijn, 1998)

The use of ecotopes enables to spatially quantify the effects of a changed flow regime, as changes in ecotopes can be related to the amount of land available to sustain a specific function. For example a change in the number of hectares of high elevated land also indicated an increase or decrease in the amount of people that can live there.

Ecotope classification, ecotope mapping and ecotope modelling have been applied in the Netherlands to gain insight in the effects of future changes in river systems (Wolfert, 2001). The advantage of using the ecotope concept in the assessment of environmental flow requirements is threefold. (1) Ecotopes are land units that are determined by various aspects and processes occurring in the landscape. These involve not only physical aspects such as erosion and sedimentation, soil development and the flooding, but also vegetation structure and fauna species, as well as crop growth and fisheries by man. Applying the ecotope concept thus allows to integrate the physical, ecological and livelihood functions of rivers into one study. (2) Ecotopes are land units that can be identified in the field and are easily mapped. Using ecotope maps, studies are made spatially explicit, so that it can be determined quantitatively (in terms of area coverage of each ecotope) where future changes will occur. (3) In the classification of ecotopes, parameters can be indicated that are related to the physical processes in the landscape and/or to management by man. This enables to model the effects of future changes in the physical or economical system on ecotope distribution in specific areas.

7.2.2 Ecotopes in the hierarchy of spatial scales

The problem with the concept of ecosystem is that it is spatially undefined: ecosystems can range in size of anything between a drop of water and the entire earth planet. Therefore, many attempts have been made to provide a hierarchical classification of ecosystems, especially for the purpose of ecological science and environmental management. One such classification is that of Klijn (1997), which incorporates several previous attempts into one logical hierarchy (see figure 7.1).

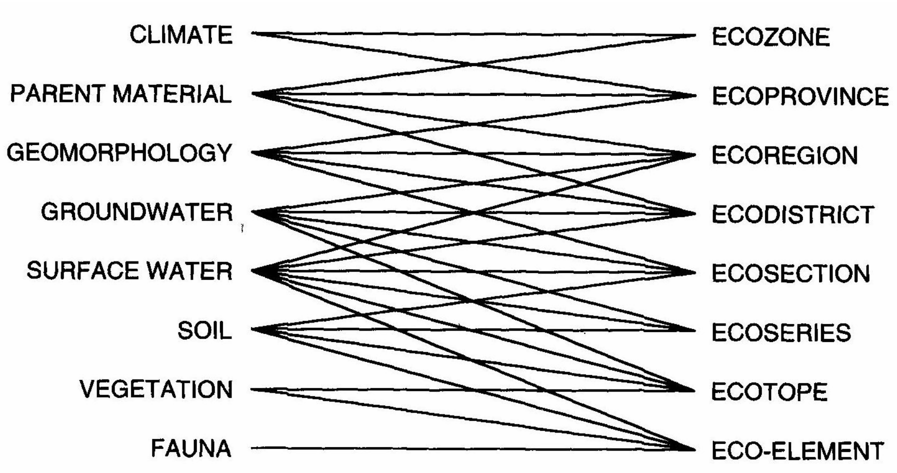

Figure 7.1: The relationship between spatial scale levels and ecosystem components (Klijn, 1997).

We see here that the ecotope is at the level of the vegetation and is primarily influenced by soil, surface water and groundwater. The spatial scales of river systems range between 10,000 km and less than a metre, and includes all the environmental factors listed in figure 7.1, from climate to fauna. When we overlay the river system scales with this ecosystem classification, it becomes clear that the ecotope ranges between the commonly used levels of river reach and micro-habitat (see table 7.1). Indeed, this is the level which is often sought for in other methods (cf. cross sections within a river reach in the Building Block Method) and compares well with the geomorphic units used by Thomson et al. (2001).

The description of ecosystems at the ecotope level includes the abiotic conditions working at this scale, i.e. ground- and surface water and soils as well as the structural characteristics of the vegetation. Major governing processes and factors are the hydro- and morphodynamics, which link up with the river flow regime (see next section), and the human activities that influence the vegetation (e.g. burning, cattle grazing or cropping). An example of an ecotope type description is that of the Dutch Water Ecotopes Classification System (WEC). Table 7.2 gives an overview of the system in which not only ecotopes but also other eco-levels are defined. At the level of larger water systems, the positional factors are the most significant: *slope*, *tidal influence* and *salinity levels*. At ecoseries level the conditional factors constitute the basis for the classification: *morphodynamics* (encompassing flow velocity, erosion and sedimentation rates) and *hydrodynamics* (timing, frequency and duration of flooding). The ecotopes are based on the ecoseries added with the operational factors *vegetation succession* and *intensity of human use* (see table 7.3). For the Dutch rivers the WEC classifies roughly 80 river ecotopes and subecotopes, which can be easily mapped and monitored (see figure 7.2). The classes for each criterion are linked to relevant ecological features of the subdivision in the WEC and categorise different ecological units, e.g. possible presence of a thermocline at a certain water depth in lakes or frequency of flooding related to vegetation in river floodplains (Wolfert, 1996).

An example of the ecotope approach in Bangladesh is given in Appendix A.

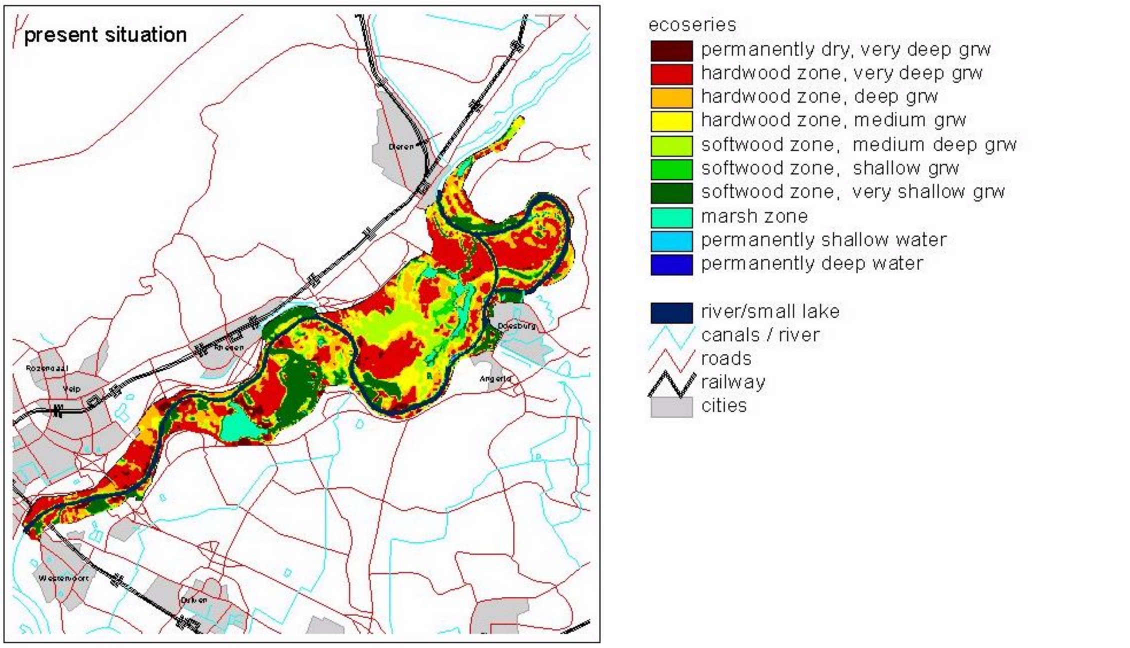

Figure 7.2: example of an ecotope map for the Dutch river IJssel.

Table 7.1 River characteristics from Frissell *et al*., 1986 matched with the ecosystem classification of Klijn (1997).

ecosystem classification according to Klijn, 1997	river classification partly using Frissell et al., 1986	typical spatial scale size [a]	typical time span of processes [a]	typical dominant processes and factors	examples
ecozone	entire river basin	1000–10.000 km	> 1000 y	climate, parent material	Nile Basin
ecoprovince	entire river basin or part of it	100–1000 km	> 1000 y	climate, parent material, geomorphology	Rhine basin
ecoregion	river stream system	100–1000 km	> 1000 y	geomorphology (drainage network development, floodplain and delta formation), altitude, groundwater flows	deposition zone
ecodistrict	river segment	100–1000 km	100–1000 y	geomorphology (river meandering), ground- and surface water, slope	floodplain landscape
ecosection	river reach	10–100 km	100–1000 y	geomorphology, ground- and surface water, slope, soils	levee, floodplain flat
ecoseries	river reach	1–10 km	10–100 y	ground- and surface water, slope, soils, bank erosion	poorly drained clay soils in floodplain
ecotope	pool/riffle system	0.01–1 km	1–100 y	ground- and surface water, changes in bed-form, soil and vegetation development	softwood floodplain forest
eco-element	micro-habitat	0.001–0.01 km	0.1 – 1 y	seasonal depth, velocity changes, accumulation of fines, soil and vegetation development	fine gravel patch

[a] Note that spatial and time scales are given here are primarily indicative for the ecosystem classification according to Klijn (1997). The scales used by Frissel et al. (1986) in their paper are on average one order of magnitude lower, because they have used scales appropriate to second- or third-order mountain streams only.

Table 7.2: Set-up of the Dutch Water Ecotope System (modified after Wolfert, 1996)

Level	discriminating factors		examples
ecosection	positional factors:	slope, tidal influence, salinity levels	river reach
ecoseries	conditional factors:	hydrodynamics, morphodynamics	poorly drained clay soils in floodplain
ecotope	operational factors:	vegetation succession, land use	hardwood floodplain forest
eco-element	biotic factors:	migration, colonisation, population dynamics etc.	birds

Table 7.3: criteria used for the classification of Dutch river ecoseries/ecotopes

Conditional factor	classes
morpho-dynamics	a. very large dynamics b. large dynamics c. moderate dynamics d. small dynamics
hydro-dynamics	0. deep water (> -1.5m) 1. permanently flooded 2. shore face 3. frequently flooded (> 100 days/y) 4. periodically flooded (100 – 20 days/y) 5. seldomly flooded (<20 days/y) 6. never flooded
land use dynamics	1. completely natural 2. natural 3. semi-natural 4. cultural

7.3 Linking ecotopes with functions

In order to determine the appropriate spatial scale and ecosystem level for study, it is necessary to consider the functions for which an EFR is to be provided. Using the key environmental parameters for each function (see table 5.4) a corresponding ecosystem level can be matched. For instance, for the production function ‘forestry’ essential processes are floodplain inundation and (in case of mangrove forests) salinity concentrations. The corresponding ecosystem level is the ecotope, where the operational factors determining vegetation growth come to expression. Likewise, for the function ‘navigation’ water depth is the major parameter, which corresponds with the ecodistrict and ecosection scales, where geomorphology, surface water and slope are the dominant environmental parameters and spatial scales of 10 to 1000 km are most relevant. For ‘recreation and tourism’ a wide range of levels may apply, going from the ecodistrict level, where entire landscapes are described (providing information on landscape amenity), up to the eco-element, where species biodiversity comes to expression. Table 7.4 provides the link between the scale levels and processes determining functions.

As can be seen from table 7.4, the ecotope level is of importance for no less than 12 river functions. In fact, only for those functions that are not dependent on the biotic conditions of the river ecosystem, ecotopes or eco-elements are not relevant. To link ecotopes with certain functions in detail, ecotope suitability rules can be used. Ecotope suitability rules enable to determine which type of land use function, that is vegetation, crop, fish, waterfowl, etc., will probably occur in which type of ecotope. Simple suitability rules can be derived from the classification and description of ecotope types. An example is given in the Bangladesh case study on the Surma-Kushiyara rivers for crops and wetland vegetation (see table A.6 in Appendix A). These are mainly based on expert knowledge and the Field Reconnaissance Survey conducted in the study area. More complex ecotope suitability rules can be derived from separate studies, such as on fish yields or vegetation growth. As an example, ecotope suitability rules for fish are given in table A.7 of Appendix A. These are based on expert knowledge, and surveys in the study area: including (1) a Fish Market Survey, and (2) a Fish Catch survey.

Table 7.4. Relevant scale levels for river flow processes determining functions

	ecozone	**ecoprov.**	**ecoregion**	**ecodistrict**	**ecosection**	**ecoseries**	**ecotope**	**eco-element**
drinking water				■	■	■		
hydro-power				■	■	■		
floodpl. agric.						■	■	
fisheries							■	■
livestock							■	
forestry							■	
hunting							■	
purification					■	■	■	
flood mitigation	■	■	■	■	■	■		
health							■	■
salt intrusion					■	■	■	
navigation				■	■			
coastline stabil.	■	■	■	■	■	■	■	
river bank stabil.				■	■	■		
gene pool							■	■
recreation/tourism				■	■	■	■	■
existence value							■	■

7.4 Linking ecotopes with river flow regime and quality

As stated in the previous section, the dominant environmental factors working at the ecotope scale are the hydro- and morphodynamics and the human activities which sometimes also are labelled as landuse dynamics. In the Dutch ecotope classification system (WEC), the hydrodynamics are worked out in terms of inundation frequencies, ranging from permanently flooded to never inundated (see table 7.3). The reason for this is that for the river systems found in the Netherlands and for similar rivers in Europe (e.g. the Danube) a strong correlation was found between the ecotopes and inundation duration. For terrestrial ecosystems, inundation especially limits the oxygen budget in the root zone. Many plant species are not able to withstand extended periods of oxygen poor conditions, thus giving rise to a reduced species diversity with increased flooding duration (Klijn, 1998). In fact there is a whole range of environmental conditions that determine vegetation growth in the river ecotopes, such as soil texture, acidity and nutrient status. But for most floodplain ecotopes the correlation between inundation frequency and these other factors is high enough to use the former as a proximate factor for the others.

A similar line of thought can be followed for the explanation of the morphodynamics. This factor is often used as an 'umbrella concept' to indicate a complex of conditioning factors and processes, e.g. flow velocity and the resulting soil texture, exposure and wave impact. There is little literature available that correlates vegetation growth with morphodynamics, usually an expert judgement is made, based on the geomorphological setting (e.g. elevation, distance to the river, landform etc.) (Klijn, 1998).

When comparing these river flow parameters used in the Dutch ecotope system with the whole range of river flow parameters and classes (cf. Chapter 5), this system is of striking simplicity. There is no mentioning of timing of the flood, no explicit reference to extreme events and no regard to the number of rises and falls. However, extreme events can be considered to be taken into account implicitly through the morphodynamics (e.g. by taking the geomorphology as a resultant of extreme high flows). In short, the Dutch ecotope system can be considered using mainly the seasonality class (but without the timing), and indirectly the extreme events class as a determinant to ecotope functioning. In part this can be explained by the fact that at the ecotope level one is predominantly interested in the vegetation structure, which makes the effect of short duration rises and falls (smoothness) less important. For the more detailed level of eco-elements (species and habitats) this approximation would certainly not suffice. Another reason for the limited use of river regime parameters is a pragmatic one: the Dutch ecotope system was not developed for assessing environmental flows, but for evaluating other types of measures, such as floodplain lowering, dike removal and side channel restoration. The river flow itself was in these cases considered to be changing not very much.

Notwithstanding the limitations given above, the advantage of the relatively simple criteria for the description of the hydrodynamics provides a good perspective for linking the spatially diverse ecotope configuration with a mathematical hydrodynamic model, as has been proven in several Dutch studies (Zeeman & Schutte, 1995; Pedroli & Rademakers, 1995, Postma et al., 1996). In the next section a procedure of ecotope modelling is provided, which has been used in the Bangladesh case study.

The typology for terrestrial ecotopes does not provide for an explicit link with most water quality parameters. Insofar as nutrients are concerned, there is no great diversity in environmental conditions in the floodplain that influence vegetation growth: the regular inundations provide for a relatively high nutrient status throughout the area. A more differentiated situation exists for stagnant water bodies within the floodplain. Salinity, nutrient status and acidity are considered important water quality factors for biotic communities, but for the Dutch floodplain water bodies a strong correlation was found between inundation frequency and these environmental factors (Van den Brink, 1990). For coastal environments the ecotope typology can easily be extended with a classification reflecting the salinity gradient.

7.5 Procedure for ecotope modelling in setting an EFR

Figure 6.2 represents a procedure which can be used in the ecotope approach for setting an EFR. Based on remote sensing images and a field survey an ecotope map of the present situation is defined. Using information from fish and vegetation surveys ecotope suitability rules are defined. These ecotope suitability rules are used in order to link the ecotopes to the presence of specific species, which are known to be both of ecological and economical importance (e.g. certain fish species that are used for food, or the presence or absence of certain mangrove trees that provide spawning habitats). A Digital Elevation Model (DEM) and a hydrodynamic model of the study area are required. The results of these two models then can be combined with the present ecotope map to define an ecotope model, using specific parameters rules. These rules are defined on the hydro-physical characteristics that result from the DEM and the hydrodynamic model, that can be linked to specific ecotopes. These rules can then be used to define the impacts of a changed hydrodynamic situation (which can be simulated by using the hydrodynamic model). Based on the resulting ecotope map of a predicted future ecotope distribution in the study area new yields of e.g. fish and crops can be calculated based on the ecotope suitability rules. This way alternative EFRs can be calculated and the impact on the riverine system can be visualised. The results of this procedure can be communicated with the river management authorities.

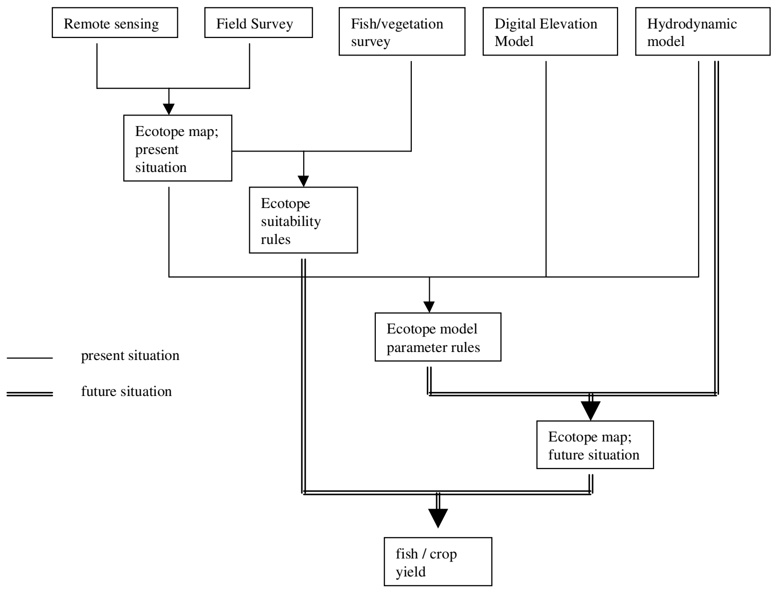

figure 6.2. Procedure for ecotope modelling

7.6 Linking ecotopes with livelihood requirements

Living along the river for many years, local people know as no other what their living environment looks like and how it has changed over the years. They have built their houses on the higher grounds and levees and exactly know which parts get inundated very often and which ones only during extreme events. But of course, they will not express this knowledge in terms of ecotope types differentiated according to the inundation frequency. Nevertheless the ecotope concept may provide a suitable framework for describing the livelihood linkages with the river. Strong points of the ecotope concept in this respect are:

- the scale of the ecotope is understandable at a local level: people think in terms of 'levees' and 'floodplain lakes' as they are recognizable elements of the landscape. They would not think in terms of a 'catchment' or 'river reach';

- the vegetation structure, as one of the main classification criteria, is easily visible in the landscape and does not require extensive knowledge of the flora or fauna;
- the inundation frequency, as another main classification criterion, is also easily understandable.

Furthermore, the fact that the landuse dynamics are explicitly considered as a classification criterion make ecotopes appropriate for use in highly modified landscapes.

Besides the advantage of ecotopes being a useful concept for translating indigenous knowledge to the scientific domain, the use of suitability rules (as described in section 7.3) provides a linkage between river flow at the one end and land use at the other. For each ecotope the suitability in terms of fish or crop yield can be assessed, which makes it possible to provide over-all landuse productivity values in both the current situation and for future scenarios, where the area extent of some ecotope types are increased to the detriment of others.

7.7 Conclusion

The use of ecotopes is a relatively new approach in setting an EFR, which may provide a breakthrough in the endeavour to integrate the large number of relevant factors currently required for modern river management. It provides an essential linkage between river regime and river functions, it allows for relatively easy quantitative prediction of future situations with respect to different scenarios of river flows and it has good communication capabilities to managers. The scientific foundation needs to be improved, and it is also clear that it is not a substitute for other methods, but rather a useful addition.

8 Conclusions and recommendations

The use of environmental flow requirements is becoming a necessary and suitable tool for river and coastal management in an increasing number of countries world-wide. Still the allocation of water for environmental purposes and the livelihood of local people is not self-evident. It has to be substantiated with quantitative and scientifically sound evidence. The methods for assessing EFR's need to be transparent in their objectives and sufficiently integrated to cover all essential elements of the river and coastal processes that sustain environmental functions and values linked to river flow. The research conducted in the ENFRAIM project has showed that:

1. only few existing methods meet the transparency and integration requirements;
2. a function approach can provide a useful tool for increasing the transparency and level of integration for setting environmental flows;
3. the full range of river flow dynamics needs to be incorporated in EFR's, in which four classes of flow parameters and their variability could be used (i.e. annual flow, seasonality, extreme events and smoothness);
4. the incorporation of local livelihood in EFR's requires an iteration between the generic function list and local stakeholders;
5. the institutional arrangements for river management need to be receptive for the flow requirements of downstream people and environment in general, including the coastal domain;
6. the ecotope concept is suitable for providing a more integrated approach, especially for dealing with the spatial variability of rivers and coastal environments.

It is clear that the ENFRAIM project could not pay attention to all aspects of EFR's in full depth. Rather it provides a general framework for an improved transparency and integration that has to be tested in the field. Therefore, a number of recommendations are formulated for future (applied) research. It is recommended that:

1. the ecotope concept is tested and applied for setting ERF's in a wide range of river settings, providing a representative picture for different geographical, environmental and social situations;
2. the scientific knowledge of the river-coast interactions is expanded to provide ready-to-use input for setting EFR's. Attention should be paid to the different aspects of the estuarine system taking into account the salt and fresh water interactions, the specific ecology and ecological functions, tidal movement and sedimentation processes. Additionally, the effect of the river discharge on the coastal system should be investigated in more detail, for example in terms of water quality. Finally, the value of the ecotope concept for coastal management can be an item for further research;
3. the institutional arrangements for incorporating EFR's, including those for downstream users are studied to generate guidelines for improvement in communication and information sharing;
4. the relations between livelihood and river flow are studied in the field in order to improve the methodological framework and to provide benchmark data for use in EFR's.

Part of this work will be continued in the on-going collaboration project between BUET and DUT (which continues to December 2004). Similar work continues in other research programmes, such as the *Catchment2Coast* project of the EU, executed in Southern Africa. It is strongly advised that Delft Cluster also continues to share its resources for this research that is considered crucial for the sustainable development of densely populated delta areas in the world.

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A Case-study Bangladesh

A.1 Selection of rivers

During the Inception Workshop of the BUET-DC cooperation programme, held in October 2001 (Dhaka) four rivers from three different hydrologic and climatic regions of Bangladesh were selected as case-studies. The selection of rivers was based on the following criteria:

1. *National interest and importance*, based on viewpoints and preferences formulated by various Bangladesh water organisations, such as the Joint Rivers Commission (JRC), the Water Resources Planning Organization (WARPO), the Bangladesh Water Development Board (BWDB) and the Bangladesh Inland Water Transport Authority (BIWTA).
2. *Regional distribution / representative for the major river systems of Bangladesh*
3. *Major problems*
4. *Variation in river characteristics and type*, such as braided or meandering, tidally or non-tidally influenced etc.

The research group decided to select the following rivers:

1. Surma and Kushiyara Rivers in the northeast region
2. Teesta River in the northwest region, and
3. Gorai River in the southwest region

An overview of the characteristics of the selected rivers is given below.

Table A.1 Overview of characteristics on criteria of the selected rivers

Selected river	national interest	regional distribution / river system	major problem	river characteristics and type
Surma-Kushiyara	part of Kushiyara river is the borderline with India	Northeast; Meghna river system	reduced Surma flow due to siltation at bifurcation point	typical middle section of river, meandering through large floodplain with many Haors (lakes)
Teesta	cross-border flow negotiations with India	Northwest; Brahmaputra river system	flow reduction due to upstream barrages	sandy, braided river with steep slope and dynamic in nature
Gorai	relations with Farakka barrage (India) and proposed Ganges barrage, World Bank restoration project	Southwest; Ganges river system	reduced Gorai flow due to siltation of Ganges/Gorai offtake	typical lowland river, meandering, partly tidally influenced (salinity gradient)

Figure A.1 Major river systems in Bangladesh

A.2 Problem analysis

Based on findings of reconnaissance visits, discussion and review of baseline situations the problems and functions of the selected rivers were analysed and are summarized. The *Surma-Kushiyara Rivers* are located in the north-east region, which is hilly and receives high rainfall. The rivers are connected to a very important wetland system, and experience flash flood in pre-monsoon period and river floods in monsoon. The rivers are still unregulated, but India has plans to build reservoirs in the upper reaches. *Teesta River* flows through the Northwest region, a very drought prone area, and is the main source of surface water in the area. Rainfall is relatively low and evaporation is high. The river has a steep slope and sandy bed. It is highly unstable and causes erosion of valuable land. The *Gorai River* is the major distributary of the Ganges and is linked with the estuary. It provides a connection between the upland fresh water discharge and brackish flow in the estuary. Its hydrology and morphology is influenced by amount of inflow from the Ganges, which receives much less flow in the dry season due to diversion at Farakka Barrage. Gorai is also influenced by tides and salinity intrusion from the Bay of Bengal.

Functions and problems of these rivers have some similarities and dissimilarities. All of these rivers provide for subsistence use of river resources, such as water for basic human needs, traditional fishing, subsistence irrigation and navigation. *Surma river* and to some extent *Kushiyara river* is a good source of construction of materials, such as sand and gravel. Mining of these materials are practised at both subsistence and commercial level. Surma flows beside Sylhet town and its flow is important for pollution abatement and municipal supply when needed. Kushiyara is navigable on a commercial scale and irrigation project has been planned to utilize water from Kushiyara. Both rivers are vital for maintaining wetland ecology. The rivers suffer from unequal distribution of inflow from their parent river called Barak, which originates in India and enters Bangladesh at a place called Amalshid, located at the northeastern border of the country in Sylhet. At the bifurcation point the Surma has completely silted up and as a consequence in dry season all flow of Barak is diverted to Kushiyara. Some corrective measure is necessary for mitigation and an assessment of instream flow requirements of the rivers would be useful.

The *Teesta* is the source of water for a large irrigation project called Teesta Barrage Irrigation Project. Mining of gravel and sand from riverbed is an important economic activity. But amount of inflow of the Teesta to Bangladesh is regulated by a barrage in India. The dry season flow is reducing causing siltation as well as harmful effect on river and floodplain. The Joint Rivers Commission is currently negotiating with India for sharing of water in Teesta and other rivers. Assessment of environmental flow requirement is necessary for such negotiation as well.

The *Gorai* is the only source of fresh water to the western part of the Southwest region, which is affected by tides and salinity. Its flow is also vital for conservation of the Sundarban, a large mangrove forest. Due to decreased upland flow in the Ganges river since 1975, the Gorai started to receive less and less water in the dry months of the year (November -May). Consequently Gorai is experiencing severe siltation and salinity intrusion problems. During 1998-2000 some dredging was done to initiate flow in Gorai. Project formulation is currently in process to construct necessary river restoration works. Answer to the question of environmental flow would be useful for the decision makers and others concerned. Functions and problems of these rivers are discussed in the next sections.

A.2.1 Surma-Kusiyara rivers

In FAP6 (1993) study local people's perception was solicited for assessment of problems related mainly to water and associated impact on their livelihood, and their suggestions for solutions. The *problems* for the upper Surma-Kushiyara area were identified as follows:

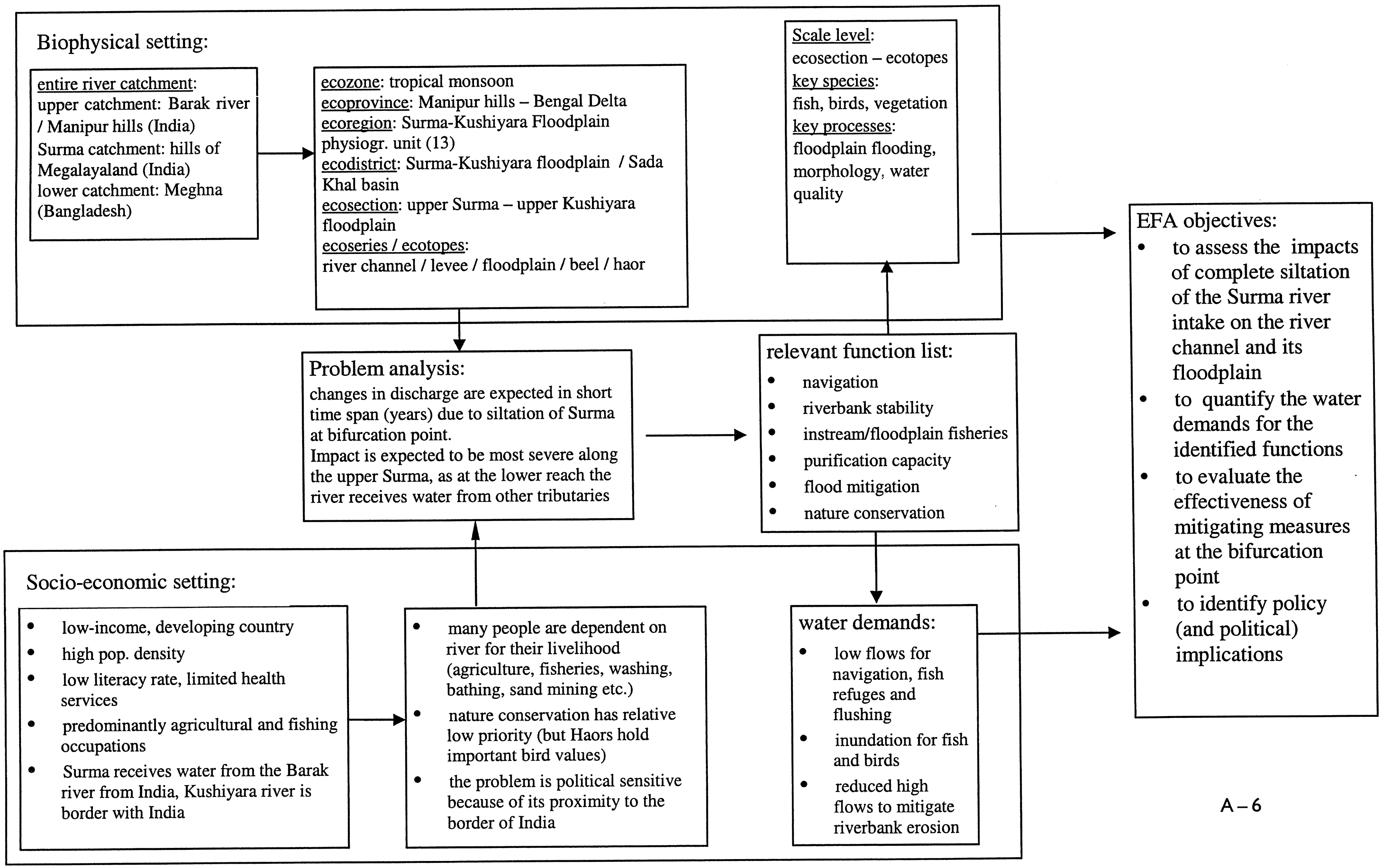
- Flood, both pre-monsoon and monsoon was described as a major problem of the area. Boro and Aus are affected by flash flood occurring between April and May. Flash flood mainly enters from Kushiyara River through various embankment breaches and open canals.
- Monson floods during July-September damage transplanted Aman, particularly in Zakiganj and Kanaighat thanas. Floodwaters enter from Kushiyara and Surma breaches in embankments, open kahals and often overtopping roads and embankments. Siltinng of Surma-Kushiyara was referred as a serious cause of flooding in the area.
- Drainage congestion is another important issue perceived by the farmers, particularly around lower beels where boro is grown. Silting of internal khals caused this problem.
- Subsistence of river resources by people and fishermen has been impaired. Difficulty in open water fishing has been caused as the water bodies are leased to influential people by the local government.
- People expressed the need for the water transportation network.

The Surma and Kushiyara rivers are connected to very important wetland areas. They feed about 30 haors including *Hakalaki* haor, and thus are crucial for ecological balance of the wetlands. Surma-Kushiyara River flow is vital for preservation and maintenance of wetland ecosystem and habitat for various species including fish. Open water fisheries in rivers, beels and haors are an important subsistence and economic activity. Connectivity of the rivers and the haors provides excellent environment for fish breeding, migration and growth. Surma and Kushiyara rivers and the internal khals are used for navigation. In the past there was a port on Kushiyara River at Zakiganj. These rivers, especially Surma is an excellent source of construction materials - sand and gravel, which are mined commercially and by individuals for living. Summarizing, Surma-Khushiyara Rivers have subsistence, commercial and environmental functions and nature conservation value as listed in Table A.2.

Table A.2 River Functions and Problems of the Surma-Kusiyara rivers

Function category	Instream function	Problems
Carrier function	Navigation	reduced flow of Surma will pose problems for navigation with country boats.
	River bank (in)stability	Kushyara river banks are expected to (or experiencing already) increased erosion
Production function	Instream fisheries	extreme low flows and seasonal no flows in Surma will damage fish stock in the river (dry season refuge function lost)
	Floodplain fisheries	reduced high flows in Surma *may* create problems for floodplain fisheries if flood duration is reduced and/or if Haors are not recharged normally. An important research question is how the floodplain environment is changed with regard to increased flows in Kushyara vis-à-vis reduced flows of Surma
Regulation function	Purification capacity / flushing of pollutants	expected to be a relatively important function. The rivers are not seriously polluted except near Sylhet town and a few industries downstream
	Flood mitigation	River aggradation in Surma *may* increase flood frequency
Information function	Nature conservation: Haors biodiversity	See also remark floodplain fisheries: much depends on how the Haor hydrology will alter when the Surma receives less water

Figure A. 2: Determination of EFR objectives for the Surma-Kushiyara Rivers



A.2.2 Teesta River

The Teesta river is the main source of surface water in the northwest region and thus vital for maintaining the riverine ecosystem. This is also the source of water for the Teesta Barrage Irrigation Project. Subsistence use of river resources, such basic human needs, fishery, navigation of country boats needs to be supported in this drought prone area. Gravel mining from riverbed is also an economic activity. Moreover, India constructed a barrage on the upper reach of the Teesta near Gajaldoba and JRC is in process of negotiation for sharing of water. The main functions and problems are listed in table A.3.

Table A.3: River Functions and Problems of the Teesta

Function category	Instream function	Problems
Carrier function	Navigation	Teesta is not a navigable route under BIWTA classification. Only country boats. Navigation constrained by low flows.
Production function	Instream fisheries	fishery is said to decline 'day-by-day'. Reason not yet clear, maybe due to barrage (reduced flows/migration barrier)
	Floodplain fisheries	Floodplain fishery is (already) limited by floodprotection works
Regulation function	Gravel mining	no problems identified
	Riverbank instability	River bank erosion and siltation is currently occurring in parts of the river. How does this relate to (future) flow conditions?
Information function	nature conservation issues	Reduced flow affects riverine ecology in drought prone area

A.2.3 Gorai river

The flows in the Gorai have been declining since the 1970s while in recent times the flow in the Arial khan has been gaining in strength. Gorai flow is essential for maintaining the ecological balance of the SW region, especially of the Sundarbans and for maintaining flows in other channels and keeping connectivity with the adjacent rivers and wetlands. Gorai flow is necessary also controlling salinity intrusion, agricultural, domestic and industrial uses, navigational facility and open water fishery.

The key functions in this river are salinity control (to keep active the industries of the adjacent area and to keep Sundarbans resourceful), navigation (even in the dry season still launch, cargo, and other goods transported boat moved in the lower reach of the Gorai River), fish (since this river is one of the important corridor for migration the fish hilsha for spawning.

The functions and problems of the river have been summarised in Table A.4.

Table A.4: River Functions and Problems of the Gorai

Function category	Instream function	Remarks
carrier function	Navigation	first 125 km will experience navigation problems due to low flows
Production function	Instream fisheries Floodplain fisheries Aquaculture Forestry (Sunderbans) Fruit trees on river banks Non-irrigated agriculture	riverine fish habitat is expected to decline; fish migration will be hampered reduced flows will result in reduction of flooplain fish habitat bagda shrimp farming would increase; golda (freshwater) shrimp farming would decrease reduction of Sundri trees would affect forestry production a reduced flowering of trees has observed due to low flows increased soil salinity and reduced freshwater flooding may impact crops
Regulation function	Prevention of salinity intrusion River sedimentation Flushing of pollutants	salinity front will go more inland (impacts on mangroves and aquaculture are described elsewhere) effect of 'tidal pumping' would increase, leading to more siltation of lower branches with consequent increase of drainage congestion etc. low flows will increase the accumulation of pollutants esp. near Khulna and Mongla
Information function	Biodiversity in Sunderbans Other	replacement of Sundri tree by other species implies a reduction of biodiversity Gangetic dolphins, birds etc.

A.3 An ecotope typology for the Surma-Kushiyara Rivers

A.3.1 Data sources

The following, spatially explicit data sources have been used for the identification of ecotopes:

- Two RS images of the Surma-Kusiyara study area: (1) an Indian Remote Sensing IRS Pan 1D image of the study area from 17 February 2002 in black and white, resolution 6 m, and (2) an IRS Liss image of the study area from 17 February 2002 in infrared colour, resolution 24 m (Figure A.3). The images are complementary as they provide different types of information. The IRS Pan 1D image provides data on topography and dry-wet soil conditions, whereas the IRS Liss image provides data on biomass and water depth.
- The sheets of BWDB contour map, officially named the Eight Inch Series. This topographical map is made by the Survey of Bangladesh (SOB). The map on a scale of 1:7920 (8 inch to 1 mile), and contains data on altitude in dm above East-Pakistan P.W.D. datum. One must be aware that the data are recorded in the early 1960s, so the altitude may have changed due to sedimentation of compaction.

- The Landform Map made by the Soil Resources Development Institute SRDI. It provides information on landforms, soils and soil suitability for agricultural purposes. The map is on a scale of 1:50,000, but less detailed compared to the RS images.
- The Base Map 1:50,000 made by the Local Government Engineering Department, which provides data on settlements, roads, and hydrological features such as rivers, canals and beels. Again, the RS images are more detailed.

A.3.2 Ecotope classification and mapping

Fourteen ecotope types covering the entire study area were distinguished, based on both RS images and the descriptions from the Field Reconnaissance Survey. Table A.5 gives a description of these ecotopes, including aspects such as vegetation or crop, soil and erosion, water depth and inundation. For the actual mapping of the ecotopes (see figure A.4) the following guidelines have been used:

- Based on the position in the field, a distinction can be made between ecotope 4: *Eroding river banks with rabi crops* and 7: *Natural levee with rabi crops*. In the RS images both ecotopes look the same, but the field expert can indicate the eroding river banks.
- The difference between *shallow* (12) and *deep beels* (13) cannot be seen on the IRS Pan 1D image, but can be seen on the IRS Liss image. The shallow parts are light blue; the deeper parts are dark blue.
- *Canal* (14) is a also a type of ecotope, which should be indicated on the map, as it is an important habitat for fish and waterfowl (birds). How canals are connected to each other, to beels and to the river can be detected from the Base map 1:50,000 , as the RS images are not always clear in this.
- *High floodplains* (9) are more or less equivalent with the stream ridges (along former river channels) within the floodplain. The difference with the *Low floodplain* (11) is best shown on the IRS Pan 1D images, so for delineation these have been consulted first. High floodplains are light grey; low floodplains are dark grey. On the IRS Liss image: high floodplains are light red or pink; low floodplains are very (deeply) red.
- The IRS Liss image shows a brown colour in some places, mostly near beels. It was concluded that these are a separate type of ecotope, *named Flood basin with Vinnya grass* (10).

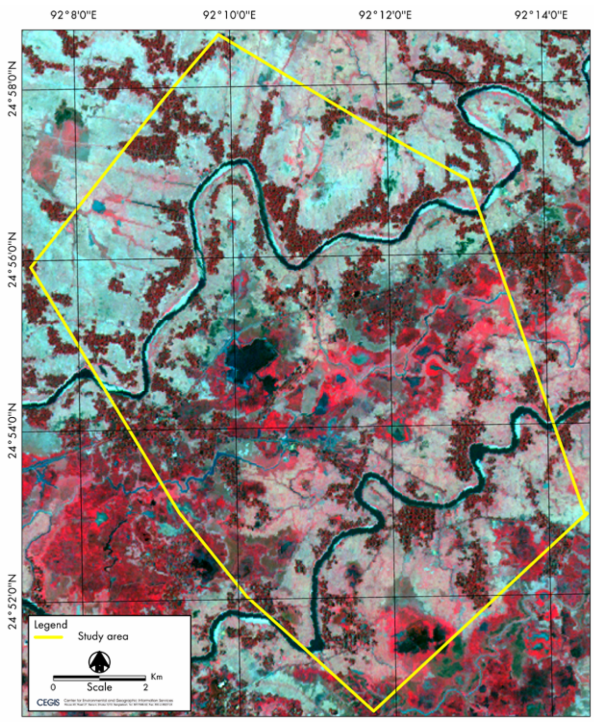


Figure A.3 IRS Liss image of the study area from 17 February 2002 in infrared colour, resolution 24 m.

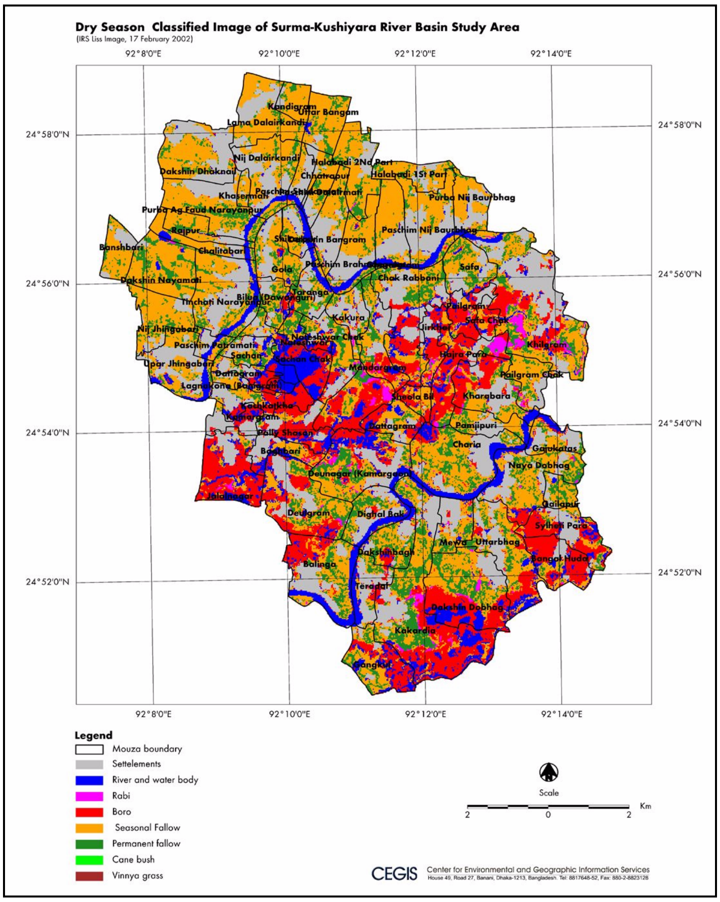


Figure A.4 A preliminary map of the ecotopes of the Surma-Kushiyara Rivers.

Table A.5. Preliminary ecotope classification for the Surma-Kushiyara Rivers

no	Ecotope	colour on IRS Pan 1D image	colour on IRS Liss image	Soil and Dynamics	Mean water depth (dry season)	Inundation (flood event)	Vegetation or crops
1	River channel	dark grey	dark blue	Coarse sand; Very dynamic	Max. 1 m, Flowing water	Part of river channel	No vegetation
2	Slough	dark grey	blue	Sand and coarse sand; Dynamic	Max. 5-10 cm, No flow	Part of river channel	No vegetation
3	Sand bar	white	light blue	Coarse sand; Very dynamic	Dry	Part of river channel	No vegetation
4	Eroding river bank	not to be identified	red	Sandy loam, Bank erosion	Dry	Part of river channel	Rabi crops
5	Natural levee with settlement	dotted because of houses and homestead vegetation, some ponds	dotted red, blue and brown	Clay loam	Dry	No inundation, except during extreme events	Timber trees, Fruit trees, Vegetables, Climbing trees
6	Natural levee with graveyard	too small to be identified	dark red, but generally too small to be identified	Clay loam	Dry	No inundation, except during extreme events	Natural vegetation
7	Natural levee with Rabi crops	white because it is harvested in December	red	Sandy loam, Bank erosion	Dry	0-30 cm*; 3-4 days during flash floods	Rabi crops
8	Natural levee with Aman paddy	white because it is harvested late November-early December	white (along the Kushyara river) to greenish blue (along the Surma river)	Sandy loam, Bank erosion	Dry	0-30 cm*; 3-4 days during flash floods	Aman paddy
9	High flood basin with Aman or Aus paddy	light grey	light red	Clay loam	Dry	30-90 cm*	Aman paddy, Aus paddy
10	Flood basin with Vinnya grass	grey	brown	Clay and clay loam	< 10 inch of water	90-180 cm*	Vinnya grass
11	Low flood basin, with Boro paddy	dark grey	deeply red	Clay and clay loam	6-10 inch of water on soil; max. 1m in the wet season due to rainfall	90-180 cm*	Boro paddy
12	Shallow Beel	deeply dark	light blue	Clay and clay loam	40 cm av. Depth; 75 cm max. depth (0-50 cm in model)	> 180 cm*	Vinnya grass, Dhundol, Chechuri, Water hyacinth, Paniaga, Sheola
13	Deep Beel	deeply dark	dark blue	Clay and clay loam	50-65 cm av. Depth; 90-110 cm max. depth (> 50 cm in model)	> 180 cm*	Vinnya grass, Dhundol, Chechuri, Water hyacinth, Paniaga, Sheola
14	Canal (Khal)	grey	blue	Clay and clay loam	0-110 cm	> 180*	Reed, Vinnya grass and Water hyacinthh

* following De Graaf et al., 2001

A.3.3 Ecotope suitability rules

Suitability for crops and wetland vegetation
Ecotope suitability rules enable to determining which type of land use function, that is vegetation, crop, fish, waterfowl, etc., will probably occur in which type of ecotope. Simple suitability rules can be derived from the classification and description of ecotope types. An example is given here for crops and wetland vegetation in Table A.6. Thus, these are mainly based on expert knowledge and the Field Reconnaissance Survey conducted in the study area.

Table A.6 Ecotope suitability rules for crops and wetland vegetation.

Ecotopes	Crops					Natural vegetation
	Timber, Fruit, Vegetables	Rabi crops	Aman paddy	Aus paddy	Boro paddy	Wetland vegetation
River channel						
Sand bar						
Slough, small fish						
Eroding river bank		X				
Natural levee, Rabi crops		X				
Natural levee, Aman paddy			X			
Natural levee, Settlement	X					
Natural levee, Graveyard						
High flood basin, Aman/Aus paddy			X	X		
Flood basin with Vinnya grass						X
Low flood basin, Boro paddy					X	
Shallow beel, Vinnya grass						X
Deep beel, big fish						X
Canal						X

Suitability for fish guilds
More complex ecotope suitability rules can be derived from separate studies, such as the studies on fish yields or vegetation growth. As an example, ecotope suitability rules for fish are given in Table A.7. These are based on expert knowledge, and surveys in the study area: incuding (1) a Fish Market Survey, and (2) a Fish Catch survey. The Fish Catch survey has been conducted in the three types of ecotopes that contain water during the dry season: River channel (Surma River: n=3; Kusiyara River: n=2), Lower floodplain (n=1), and Beel (n=6). When more data are available, also the fish yield or the fish catch per effort can be determined for these ecotope types.

Table A.7 Ecotope types as habitat for fish guilds

Ecotopes	**Fish Guilds**					
	Snakehead	**Catfish**	**Clupeids**	**Carp**	**Perch**	**Miscellaneous**
River channel		X	X sometimes	X		Eel, Goby, Notopterids
Sand bar		X small		X		Goby
Slough, small fish		X small		X small		Goby, Prawn small
Eroding river bank		X breeding		X small		Goby, small Prawn, other small fish
Natural levee, Rabi crops						
Natural levee, Aman paddy						
Natural levee, Settlement				X in ponds		
Natural levee, Graveyard						
High flood basin, Aman/Aus paddy	X	X	Only Chapila	X	X	Eel and other
Flood basin, Vinnya grass	X	X small	Only Chapila	X small	X	Eel and other
Low flood basin, Boro paddy	X	X	Only Chapila	X	X	Eel, Notopterids and other
Shallow beel, Vinnya grass	X	X small	Only Chapila	X small	X small	Eel and other
Deep beel, Big fish	X	X	Only Chapila	X	X	Eel and other
Canal	X	X	Only Chapila	X	X	Eel and other

Note: Chapila = Chudusia chapra

More detailed ecotope suitability rules can be determined from the vegetation survey, as this gives insight in the different growth of fruits and plants in the various ecotopes. Trees on natural levees, may suffer form dessication: dryer soil effects the growing of trees and the ripening of fruits. This is obvious from the vegetation survey, conducted in a few types of ecotopes. It is advised to select only a few species for this survey, which are sensitive for hydrological change, and are relevant to the local people.

B Ecotope modelling: case study Maas (The Netherlands)

B.1 Introduction

As the use of the ecotope concept is a relatively new approach in setting an EFR, a separate study on the River Maas in the Netherlands was used to explore the aspect of ecotope modelling. Like the case study in Bangladesh, the ecotopes provided an essential linkage between river regime and river functions in a quantitative prediction of future situations with respect to different scenarios. Different is that floodplain management measures were evaluated here, whereas in the case study in Bangladesh the effects of future changes in discharge were studied. However, the ecotope modelling procedure applied is more or less the same.

B.2 Background

From point of view of river management and risk prevention, changes in the river system historically focused on introduction of measures. Building dikes and groynes en managing the roughness of the floodplain vegetation are some examples of classic engineering practices in the Netherlands. More and more, however, river management becomes part of an overall landscape planning process, especially in densely populated areas where various stakeholders are involved. History shows that neglecting the occupation of floodplains and all of its interactions with agriculture, nature conservation, recreation or forestry still causes damage by flooding and is not sufficient at all. Technical concepts therefore have to be integrated with planning concepts, both in plan design and plan evaluation.

To copy the complete planning process into an fully automated environment is nearly impossible. Brainwaves or complicated interactions between designers, technical assistance and policymakers are difficult to understand and do need a more sociological approach. However, some parts of the planning process are similar in most planning processes an can be stored in rules. In figure B.1 a simplified way of planning is described. Most plans are dealing with two types of planning components: measures and land use targets (or land use values). Measures are meant as technical measures linked to the abiotic conditions (e.g. building dikes) or abiotic management (e.g. lowering the groundwater table). Targets are meant as land use changes or biotic management changes. To achieve targets (e.g. good drained arable land), sometimes technical measures are necessary like digging channels. On the other hand sometimes measures can be taken on their own.

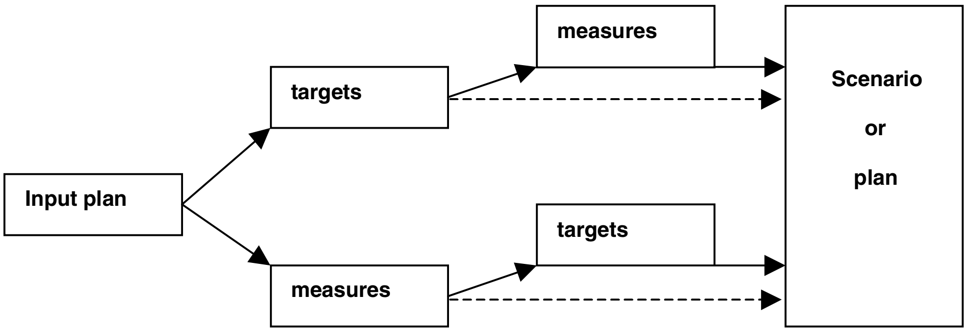


Figure B1. Targets and measures in plans

Planning mostly starts with some goals that have to be achieved in future. Sometimes planning starts with realistic plans or simply a range of measures. However, despite the input, in general all the plans in practice are checked with stakeholders and afterwards there is an environmental or abiotic check and evaluation.

B.3 Aim of the case study

This case study focussed on the effect of a river management measure on agricultural land use values. The study was part of investigations on the effects of future climatic change, that will cause an increase in discharge of the River Maas. Stripping the floodplain surface is seen as a measure to prevent future flooding. A measure like this is likely to change soil type en flooding frequency of floodplain land and thus obligates the river manager to investigate the effects on agricultural use. In this case the research question was translated into scenarios:

> *Strip the surface of all the floodplains of the Maas down to 3 meters with steps from 0.5 meter and assess the effect of each scenario for agricultural landuse. Determine critical levels at which possibilities for agricultural landuse value will change dramatically.*

B.4 The LEDESS model in detail

In 1996 the former DLO-Staring Centre (now Alterra) developed LEDESS (Landscape Ecological Decision & Evaluation Support System) which was used in several projects and even made specific for river management (Eupen et al., 2002a; Eupen et al., 2002b). LEDESS is an example of a GIS and grid based expert system. It is a computer model used to assess and evaluate scenarios to see if these are possible from an ecological viewpoint and to determine their consequences for nature and/or their economic effects. This way, choices can be made on what kind of nature type is desired and the suitability of the location as well as the economic profitability. The landscape-ecological modelling in LEDESS is based on a simplified view of ecosystems. Four components are considered, namely landscape, physiotope, vegetation and fauna, furthermore their interactions are taken into account (Table B.1). The relations are topological (vertical) and chorological (horizontal). Processes are present as a derivation from the different ecosystems, in other words they are not explicitly present.

Table B.1 Excerpt of the ecotope classification used, showing relationships between aspects of soil, flooding, vegetation and land management.

Ecotope	**River regime**		**Vegetation / land use**	
	Soil type	**Flooding frequency**	**Type**	**management**
Agricultural grassland	Clay	20 – 50 d/year	Grassland	agricultural
Natural grassland	Clay	80 - 150 d/year	Natural grassland	natural vegetation
Agricultural crop a	Clay	50 - 80 d/year	Wheat	agricultural
Agricultural crop b	Sand or Loam	0 d/year	Potatoes	agricultural
Dry Forest	Sand	< 30 d/year	Forest	natural vegetation
Reed marsh	Sand or Clay	> 150 d/year	Reed Marsh	agricultural

Within LEDESS for three of the four components separate modules are designed. A system of knowledge tables and typologies connects these modules.

- The SITE module checks the ecological consistency of a nature target plan by comparing the needed abiotic site conditions with the present abiotic site conditions. For areas which are not suitable, measures can be applied by the user to modify the present situation into suitable site conditions (e.g. by excavation or raising the groundwater level).
- The VEGETATION development can be simulated. Based on abiotic conditions and management, the user defines the number of years that the vegetation is allowed to develop and which nature target plan is used. A second, simpler option is the snapshot development: a nature target plan is directly translated into an end-vegetation structure. The economical effects of the physiotope and vegetation stucture change can be calculated as well.
- Suitable FAUNA habitats are calculated, based on vegetation and physiotopes (abiotic conditions). Additionally, disturbance buffers may be placed around e.g. roads and cities. Finally, the size of the habitat clusters can be calculated to show how many animals can live in a cluster.

Every module results in a map and generates data for the next module. With the results a (nature development) plan can be adjusted or a choice can be made between different scenarios.

The LEDESS-input consists of geographical data and knowledge tables. The present situation (soil/physiotopes, vegetation structures) and plans (nature targets) are stored as geographical data. By combining different data layers new (geographical) data can be calculated from relevant knowledge matrices. The link between the maps and classifications is made with knowledge tables (figure B.2). A knowledge table consist of a matrix of the two factors on the X- and Y-axis. Every combination of those two results in a third factor. So, a knowledge matrix represents a set of rules-of-thumb describing a new condition resulting from two existing conditions (expert knowledge).

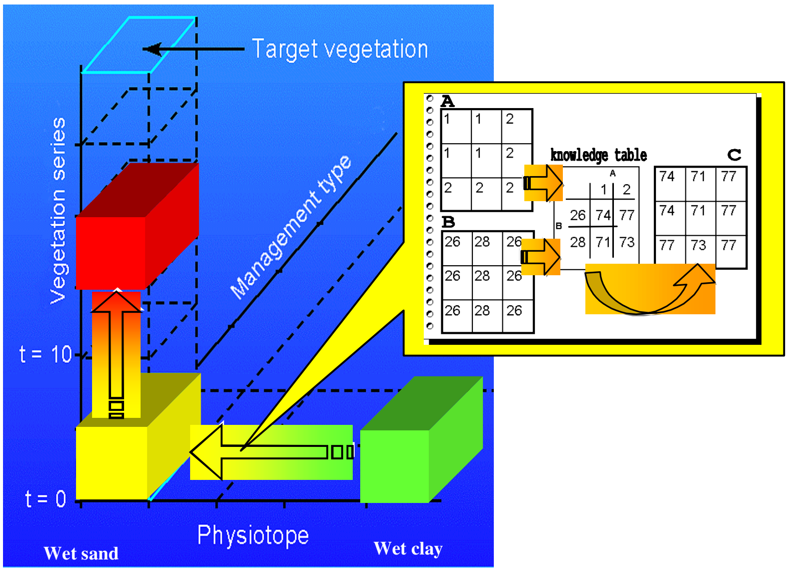


Figure B.2 Mechanism of LEDESS knowledge tables. Two maps (left in box) with values related with a knowledge table (middle) calculates a new map (right).

To predict agricultural values related to stripping the floodplains, a specific knowledge table had to be developed. The HELP knowledge table has been developed to predict the relative agricultural production values of soil types compared to production levels on optimal water-en nutrient availability (Koerselman, 1987). The production defining factors are the availability of water the type of soil. The HELP method expresses the production loss by water shortage or water surplus in percentage compared to the theoretical maximum production of 100%. For calculating agricultural values of floodplains a production depression-factor "flooding" has been added:

$$100 \times (1 - \text{depression water surplus}) \times (1 - \text{depression water shortage}) \times (1 - \text{depression flooding})$$

B.5 Results of the evaluation

For each combination of soil type and flooding frequency a HELP depression factor has been calculated and stored in the LEDESS knowledge table. Soil type and flooding frequency are each strongly related to surface height and therefore with the amount of the stripping the surface of the floodplain. Figure B.3 shows a part of the resulting maps for the effect of stripping the surface with 0.5 m and 2 m. There are differences between the river reaches, due to differences in soil type and height above the surface, which influences the flooding frequency (figure B.4).

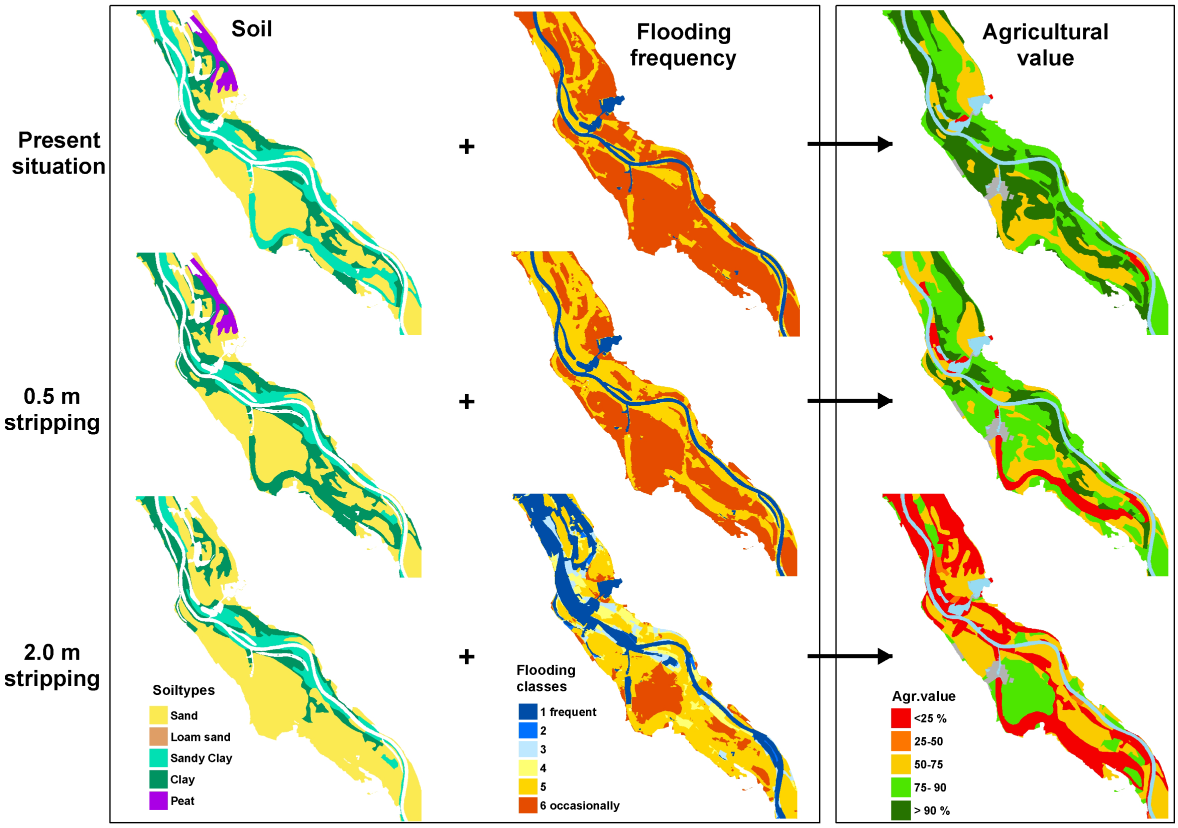


Figure B.3 Resulting maps of the effect of stripping the floodplain surface with 0.5 m and 2 m for grassland.

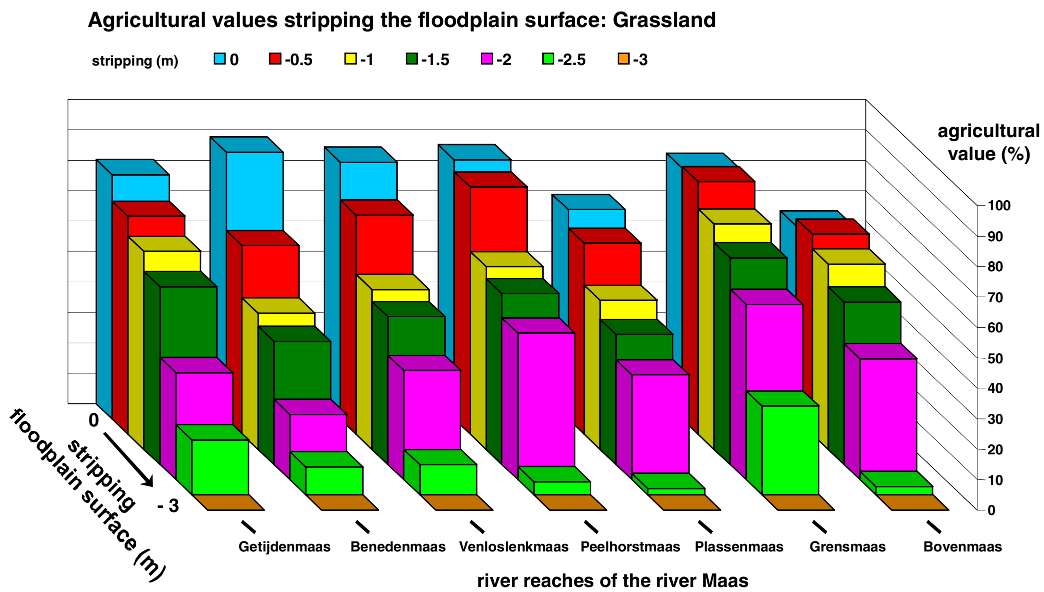


Figure B.4 Summarised results for Grassland for all river reaches of the river Maas.

B.6 Conclusions

The study results clearly show that stripping the surface of the River Maas floodplains has a strong negative effect on the agricultural land use values. Moreover, the spatially explicit method enabled to indicating where the effects are relatively large or small, as well as to determining critical levels at which the agricultural land use values drop dramatically. Being based on a simplified view of ecosystems and requiring knowledge that can be easily provided by local researchers, the ecotope modelling approach is likely to be useful for the establishment an EFR in other areas and countries too.

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General Appendix: Delft Cluster Research Programme Information

This publication is a result of the Delft Cluster research-program 1999-2002 (ICES-KIS-II), that consists of 7 research themes:
►Soil and structures, ►Risks due to flooding, ►Coast and river , ►Urban infrastructure, ►Subsurface management, ►Integrated water resources management, ►Knowledge management.

This publication is part of:

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		IHE		
		TUD		
		Royal Netherlands Embassy, Dhaka, Bangladesh		
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Number of involved PhD-students	:	2		
Number of involved PostDocs	:	0		

Delft Cluster is an open knowledge network of five Delft-based institutes for long-term fundamental strategic research focussed on the sustainable development of densely populated delta areas.

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