Challenge Program on
Water and Food
Background Paper 3

The Contribution of Aquatic Ecosystems and Fisheries to Food Security and Livelihoods: A Research Agenda

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Introduction

Aquatic ecosystems are a diverse group of water dependent habitats (box 1) that support important biodiversity and provide a wide range of benefits to people (box 2). As pressure on the world's water resources has increased, there has been growing concern that increased investment in water management needs to include investments to sustain these aquatic ecosystems and the benefits they provide. This is particularly so where these systems are used intensively by poor communities, mainly fishers and pastoralists, and are therefore of critical importance for efforts to sustain and improve these rural livelihoods.

This concern was well reflected in the second World Water Forum (2000) and in the World Water Vision, and is a major focus of the Dialogue on Water, Agriculture and Environment. Yet, building upon this growing international recognition and moving forward to achieve real change and improved management at national and local levels will require policies, institutions and governance arrangements that embrace these concerns, together with greatly strengthened technical capacity to design and implement innovative approaches to maximising value. For example,t if the pastoral and fishery production of riverine floodplains is to be sustained in the face of increasing demand for water, and their contribution to improved food security and livelihoods is to be maximised, effective institutional arrangements to help govern these ecosystems and their resources need to be established and empowered. Similarly, the governance regimes for the river and lake basins, or coastal zones, within which these aquatic ecosystems lie need to take account of the importance of these ecosystems and their requirements, in particular for specific quantity and quality of water throughout the year. Without such improved governance, information on the value of the resource, on technologies to sustain and enhance this value, and on environmental flow requirements will be of little lasting value.

In turn if new policies, institutions and governance arrangement are to be truly effective and for them to lead to sustainable improvements in the management of aquatic ecosystems and fisheries, they will need to be well informed. While the need for better information applies to many issues, there are three questions where this is particularly important:

1. What is the full value of aquatic ecosystems and the trade-offs amongst different water uses?

2. How can water productivity be increased by incorporating the values of aquatic ecosystems and improving their management?
3. What are the environmental flow requirements (including water quality) required to sustain aquatic ecosystems and the goods and services they provide to people?

In the absence of such information, planners tend to assume that the value of these resources and their contribution to productive water use is low or negligible, and that consequently their flow requirements are not worthy of consideration. Conversely, the stakeholders who use these ecosystems and depend upon their values, are unable to promote their needs effectively relative to agriculture, industry and commerce (Sverdrup-Jensen 1999). In most cases this leads to the loss of sustainable goods and services that the natural aquatic systems offered to rural populations, shifts benefits towards other more restricted and favoured social groups, and contributes to increased local poverty and emigration towards urban centers (Tisdell 1999).

In recogntion of this analysis the aquatic ecosystem work of the Challenge Program (CP) on Water and Food will seek to develop and apply systems of management that sustain and, where possible, enhance the benefits to people from these systems as an integral part of approaches to improving water productivity at the basin level. It will do so through analysis, development and dissemination of tools and methodologies that will foster effective governance of aquatic ecosystems and their resources. This will be done through development, application and dissemination of tools that will provide quality information on the value and water requirements of these ecosystems and ways to enhance their productivity, and by strengthening the capacity to use these tools and techniques. To help ensure that this process begins by focusing on clear priorities, the present paper examines issues of governance, valuation, productivity and flow requirements and sets out the research questions that require immediate attention.

Box 1. Principal aquatic ecosystems.

Streams and ***rivers*** are flowing waters while ***floodplains*** are the lowland areas, adjacent to watercourses that are subject to periodic or near-permanent inundation and sediment deposition. Streams, rivers and floodplains support substantial inland fisheries and have potential for enhanced fisheries, while many floodplains are important for pastoral production and flood recession agriculture.

Reservoirs are artificial waterbodies, primarily used for irrigation, hydroelectric power and domestic water supply. ***Lakes*** are natural waterbodies. Both, are usually freshwater and have high potential for aquaculture and conventional or enhanced capture fisheries. Small water bodies are also lentic habitats less than 10 km^2 in surface area.

Ponds are small freshwater bodies, usually artificial, occasionally natural, in rainfed and irrigated areas where aquaculture, particularly integrated with agriculture, is possible.

Estuaries are partially enclosed coastal bodies of water which are either permanently or periodically open to the sea and within which there is a measurable diurnal and seasonal variation of salinity due to the mixture of sea water with fresh water derived from land drainage (after Day 1980 and Day et al. 1989). They include key habitats, such as mangroves, that support coastal fisheries.

Lagoons are coastal, lacustrine waterbodies that are influenced by both land drainage inputs and marine inputs. They are similar to estuaries in their diurnal and seasonal salinity and tidal patterns.

Wetlands as defined by the Ramsar convention include a wide variety of habitats such as marshes, peatlands, floodplains, rivers and lakes, and coastal areas such as saltmarshes, mangroves and seagrass beds. Also, coral reefs and other marine areas no deeper than six metres at low tide, as well as constructed wetlands such as waste-water treatment ponds and reservoirs are defined as wetlands (Ramsar Convention Bureau 2000). This definition of wetlands therefore includes all of the specific ecosystems listed above together with many other smaller freshwater ecosystems and open coastal waters less than six meters deep.

Ricefields are man made aquatic agro-ecosystems that cover extensive areas of the tropics, sub-tropics and warm temperate regions. In addition to their primary function of rice production, ricefields in many countries are extremely important sources of fish and other aquatic animals and plants for human consumption.

Box 2. Benefits of aquatic ecosystems.

FAO statistics indicate that each year some 8 million tons of fish are caught from freshwater ecosystems and 18 million tons of fish are produced from freshwater aquaculture (FAO 1999). The capture fish production of the lower Mekong basin alone totals some 1.5 million tons annually amounting to a total retail value of US$ 1.4-1.7 billion (MRC 2001), while catches in Lake Victoria reached over 500,000 tons in the 1990s. In sub-Saharan Africa the larger floodplains including the inner delta of the Niger, the Sudd of the Nile, and Lake Chad each yield up to 100,000 tons per year and generate annual income in excess of US$ 20-25 million (e.g., Quensière 1994). These floodplains also support extensive pastoral production. For example, the inner delta of the river Niger supports 5 million head of cattle and small livestock every year accounting for 10 percent of the country's gross national product (GNP).

The biodiversity value of wetlands is also high. In west Africa the floodplains of the Senegal, Niger and Chad basins support over a million waterfowl, many of them migratory, throughout the year (Monval et al. 1987). In Zambia the Bangweulu basin supports 30,000 black lechwe, along with Africa's most important population of sitatunga and shoebill storks. In Brazil, the Pantanal covers over 10 million ha, with large populations of caiman, capybara, and jaguar, as well as one of the most distinctive mosaics of vegetation in Latin America (Prance and Scaller 1982)

The economic value of this biodiversity is difficult to quantify, but in many places it is the focus of a successful tourist industry. For example, Botswana's Okavango Delta brings in US$ 250 million worth of foreign exchange each year and is the principle source of livelihood for many people in the north of the country including the country's third largest town, Maun.

Important ecological services derived from aquatic systems include habitat and nutrients for consumed species, protection of adjacent lands from erosion, siltation, storm damages, floods and droughts; nutrient cycling; tourism and recreational value; carbon sinks and gas regulation. A global study (Costanza et al. 1997) has indicated that about 83 percent of the global value of ecosystem services come from marine waters, wetlands and lakes/rivers; the total economic value of these ecological services was estimated at US$ 21 trillion.

The Research Agenda

RATIONALE

The primary objective of the CP on Water and Food with regard to aquatic ecosystems is to:

- Enhance food security and livelihoods by maintaining aquatic ecosystems and optimizing fisheries.

In pursuit of this objective the overarching research question upon which the aquatic ecosystem component of the CP will focus is:

- How can aquatic ecosystem services be maintained and fisheries also be optimized?

It will do this by addressing a set of more specific research questions derived from analysis of, and directed towards, four major groups of issues: policies, institutions and governance; valuation; water productivity improvement and environmental water requirements.

POLICIES, INSTITUTIONS AND GOVERNANCE

There is growing recognition that many of the policies, institutional and regulatory arrangements governing use of natural ecosystems and their resources have lead to inefficient and inequitable allocation of these resources and loss of their benefits to people. As a result there is today growing investment in the development of more efficient policies and governance regimes for these natural resources, most noticeably of fisheries, forests and wildlife. This is particularly so in light of the processes of decentralisation that are currently being pursued in many countries (UNDP 2000).

However, there is a wide gulf between this recognition of the need for change and identification of the specific actions that need to be taken. In many developing countries, policy-making and implementation systems for aquatic ecosystems and their resources are not clearly understood. There is ,therefore, an urgent need to better understand these policy making processes as a basis for improved governance of these resources.

In light of this analysis the key research questions are:

1. What are the factors that influence people's access to, and control over, aquatic ecosystems and their resources?

2. What kinds of governance systems and enabling policies and institutions foster equitable and sustainable management of aquatic ecosystems?
3. How can capacity be built within national and local institutions to understand the livelihoods of poor people and their use of aquatic ecosystems, and take account of their needs in policy development and governance processes?
4. What knowledge systems are needed to help build this capacity and support development and application of these policies, institutions and governance systems?

What are the factors that influence people's access to, and control over, aquatic ecosystems and their resources?

Clearly defined and enforceable access rights are a pre-requisite for effective governance. Yet only rarely are the factors determining access to aquatic resources by different communities and social groups well understood. Better understanding of these access rights is an essential pre-requisite for the design of effective governance systems. To achieve this access rights will need to be examined in a diversity of ecological, social, economic and institutional settings.

In particular the ways in which hydrological change and shifts in the availability and diversity of fish and other resources influence patterns of exploitation (e.g. differential impact on men/women/children, motorised/manpowered fishermen, different ethnic groups, depending on the fraction of the resource they utilize) need to be understood. In some resource systems property rights change with the seasons with seasonally flooded fields acquiring common property conditions during the rainy seasons and private property conditions during the dry seasons. Such seasonality in access or availability of aquatic goods and services, and complementarity with other activities (such as access during periods of low agricultural production) is especially important.

Specific research questions in this area include:

- How is access to aquatic resources regulated in different aquatic ecosystems?
- How have these access rules changed in response to environmental, demographic and economic change?
- How do hydrological changes alter access to aquatic resources?
- What other external factors will change access?

What kinds of governance systems and enabling policies and institutions foster equitable and sustainable management of aquatic ecosystems?

At present effective governance over aquatic resources is the exception rather than the norm in most developing countries. If access by the poor to aquatic resources is to be improved, and management of these resources is to be sustainable, major reform of aquatic resources governance, policies and institutions is needed. Efforts to improve policies and systems of governance, and to strengthen institutions, will need to be grounded in a better understanding of how these policy-making processes function, how responsibilities for managing aquatic resources can be shared between government and community organisations, how different stakeholder groups in society affect policy-making and implementation, and how improved information can result in decisions that benefit the poor.

A major constraint to effective policy making in many developing countries is that the majority of society are usually excluded from any involvement in the policy-making process. As a result policy decisions frequently favor certain powerful sectors of society, rather than wider society and especially the poor. This is especially so when the poor are located far from urban centers, as is the case for many of the rural communities dependent upon aquatic resources. To address these concerns new approaches, and frequently new institutions, are needed to manage aquatic resources. In most cases these need to be developed through effective interaction between communities, government and non-governmental organizations.

There is a growing volume of experience in establishing and managing these institutions. However, in order that this encouraging progress can lead to greater impacts, they need to be pursued in a much wider range of social, economic and environmental contexts. In addition, more effective ways to learn and apply broadly applicable lessons from specific examples need to be found. The lessons of these specific case studies need to be harnessed, scaled up and applied over much larger areas.

Specific research questions in this area include:

- Where are the governance systems that foster equitable and sustainable management of aquatic resource systems (ARS)?
- How can national institutions best harmonize across the international boundaries of large international river basins?
- What are the best types of institutions for dealing with water and aquatic resources management in international river and lake basins?
- Does the level of devolution of governance to the local level influence the conditions of the aquatic ecosystems and wellbeing of those who depend upon their resources?

- Do policies that are developed through a more participatory process with the major stakeholders of the aquatic resource system perform better in terms of environmental, economic, social and development indicators?
- Do more participatory based institutions lead to fairer allocation of benefits from aquatic resources, resulting in more sustainable institutional arrangements?
- What types of participatory processes best foster effective policy making?
- What incentives and other mechanisms can be used to change the system of governance to better serve poor stakeholders?
- What tools, methodologies and management approaches are most effective in taking the lessons from site specific case studies and applying these at a larger scale?

How can capacity be built within national and local institutions to understand the livelihoods of poor people and their use of aquatic ecosystems, and take account of their needs in policy development and governance processes?

Efforts to improve policy making processes need both to be grounded in a better understanding of how these policy-making processes function, and sustained by building the capacity of national institutions to pursue research and extension approaches that will favour these community focused approaches. However, at present, most national institutions have little capacity, and often even less incentive, to invest in understanding the needs of poor fishers and pastoralists often living many hundreds of kilometers from national capitals. Ways to strengthen capacity to do this need to be found and fostered.

Specific research questions in this area include:

- How can livelihood analyses become part of the remit of institutions involved with managing and sustaining aquatic ecosystems?
- What institutional structures, and research and extension approaches, have proved to be most effective in building national capacity to work with poor rural communities using aquatic ecosystems?

What knowledge systems are needed to help build this capacity and support development and application of these policies, institutions and governance systems?

The information systems that sustain effective governance of aquatic ecosystems (and other natural resources) are critical. The conventional view of policy-making and implementation assumes that policy-makers will utilise new information and better understanding to improve policy design for the benefit of society. In this situation, research and research scientists provide information for policy-makers, who make policy decisions and then hand these decisions down to administrators (managers) for implementation through various management arrangements. However, in many developing countries, policy-making and implementation systems do not function in this way. Instead, many decisions are taken to favour certain powerful sectors of society, rather than for society's benefit as a whole. These problems are compounded by the fact that much of the current information available on poor people's livelihoods and natural resource management issues tends to be disseminated within limited networks. At present technical information gathering and dissemination is mainly in print, often in English, and usually packaged for presentation to a fairly well defined audience. In contrast most poor people tend to share knowledge through local language text, and oral and visual communication systems. As a result natural resource users are frequently prevented from participating in technical information networks. More flexible, decentralised systems of information exchange are therefore required.

Specific research questions in this area include:

- What knowledge base is needed to drive improved governance systems?
- How can this best be structured to ensure delivery to poor stakeholders?

VALUATION OF ECOSYSTEM GOODS AND SERVICES AND THE COSTS OF DEGRADATION

The development and effective application of improved policies, institutions and governance systems for aquatic ecosystems and fisheries needs to be supported by better information on the value of different aquatic ecosystems and their resources. Only rarely however is this information available, and much of the existing data are fragmentary, dispersed and dated. Even for fisheries, which are generally the best documented aquatic resource, there is widespread scepticism as to the accuracy and relevance of current statistics, most of which are collected from a small number of monitored landing sites, an approach of limited value in assessing the importance of riverine freshwater fisheries in the tropics (van Zalinge et al. 2000; Baran and Guttman, in prep.). In many freshwater fisheries, actual catches are believed to be at least twice the reported figures (FAO 1999; Welcomme 2001). There is therefore an urgent need to improve the quality of information available on the use made of these ecosystems and their resources by different communities and social groups, on their consequent economic and social values, and their contribution to sustaining, or potentially enhancing, livelihoods, reducing poverty, and improving food security, and the potential cost to society of the impacts that result from degradation of these systems. At the same time, greater capacity to effect such analyses needs to be developed wherever such information will assist in improving governance and the quality of decision making about aquatic ecosystems and water use.

In light of this analysis the key research questions concerning valuation include:

1. What are the monetary and non-monetary values of the goods and services provided by different types of aquatic ecosystems, and what proportion of the household/community economy do they comprise?
2. What are the social and economic costs of degradation of aquatic ecosystems and decline and loss of their goods and services?
3. What are the appropriate tools to generate this information rapidly and for use by poor stakeholders?

What are the monetary and non-monetary values of the goods and services provided by different types of aquatic ecosystems, and what proportion of the household/community economy do they comprise?

Different types of ecosystems have different values and these vary according to the specific biological characteristics of individual sites and the way they are used by people. The range of these values, and the reasons for their value need to be better understood. To help achieve this, a series of comparative case studies in different ecosystems and different localities varying in characteristics such as methods of water usage (regulated versus non-regulated) and means of exploitation of aquatic production (e.g., rice fields, aquaculture, etc., compared to "non-cultured" and flood systems) are required. The specific household contribution of aquatic ecosystems needs to be documented: who uses the resources, how, and when?

Specific research questions in this area include:

- What is the value of ecosystem goods and services in the livelihoods of poor communities dependent upon natural resources?
- What is the value of fish production from natural aquatic ecosystems for livelihoods and food security?
- How does this compare with alternative uses of the fishery resource?
- What is the value of other food produced by these ecosystems?

What are the social and economic costs of degradation of aquatic ecosystems and decline and loss of their goods and services?

Balancing the multiple and competing demands for water is one of the greatest challenges facing water managers. In the past, the wider costs of water abstraction, particularly those affecting the environment and borne by economically-weak communities of people, have been ignored. As a general rule, the overall benefits from abstraction of water increase to a point, beyond which the aquatic ecosystems degrade significantly, valuable resources and services are lost, and costs are incurred as changes to the ecosystems begin to affect the health and well-being of local communities. However, in only a relatively few cases have these costs been assessed fully. Also the tools and capacity to predict such costs are limited. Greater investment in such assessment, and in development of these tools and capacity, is therefore required.

Specific research questions in this area include:

- What has been the impact on the livelihoods of different communities and social groups of degradation of specific aquatic ecosystems and their resources?
- How do these impacts vary with ecosystem and resource type, and with social and economic status of the communities?
- What tools and methodologies are most effective in analysing and predicting these impacts?

What are the appropriate tools to generate this information rapidly and for use by poor stakeholders?

At present economic valuation studies of aquatic ecosystems tend to be carried out in an intensive manner. This approach tends to involve one or more scientists visiting an area, meeting with communities, undertaking surveys, and then going off to analyse data and write a report. While these are immensely valuable and have played an important role in beginning to help build awareness on these ecosystems, and while further work at this level will be carried out through the CP, simpler systems need to be developed so that they can provide information more directly to communities and other key stakeholders on an ongoing basis. This may involve long term monitoring of certain key parameters, or the establishment of research networks for individual rivers or other large aquatic systems.

Specific research questions in this area include:

- What needs to be done so that existing valuation techniques can be made more readily applicable in developing countries with limited institutional research capacity?

- What is the critical information that is required by decentralised governance systems?
- How are can this be generated on a regular and reliable basis?
- Are existing tools used by developed countries transferable directly to developing countries?

ENVIRONMENTAL WATER REQUIREMENTS

Processes such as the World Water Vision, the Global Water Dialogue and the World Commission on Dams (WCD), have led to increasing awareness of the need for new approaches to managing water productivity at the basin level. For example, guidelines 15 and 16 of the WCD call for, "Environmental Flow Assessments" and "Maintaining Productive Fisheries" and specify, *inter alia*, the importance of assessments of the water requirements of fish populations, and the mitigation of fish losses in downstream floodplains through flow releases. In order for the awareness and policy frameworks generated by these and other international initiatives to engender sustained benefits for poor communities dependent on aquatic ecosystems, they must be supported by policy-relevant information to assist water-management decisions at local, national and regional level. In particular, there is an urgent need in the developing world for accurate information on the volumes and distribution of water required to sustain these ecosystems, including the different levels of ecosystem benefits that such flows would support, to allow for more informed decisions on the equitable use of water.

If the need for improved and timely information on water requirements is to be met, tools and methods relevant to the needs and context of developing countries need to be sourced or developed. For such tools to be truly useful, they should use information that is easy to collect and yield information that is both relevant and easy to convey to all stakeholder groups. While there is potential to build upon experience in the North, where the past decade has seen the development of a wide range of approaches for assessing environmental water requirements, many of the tools developed there are dependent on the substantial knowledge base and research capacity available in many Northern countries, or have been designed to meet the specific needs of national regulatory frameworks. While of considerable academic interest, most of these techniques are of limited practical relevance to the current needs of developing countries. In addition, much of the work has been done in temperate climates, and in small streams and rivers, and the applicability of the resultant techniques to larger tropical rivers is questionable. The type of information generated by environmental water assessments, and channels for its delivery to poor stakeholders in decentralised institutional arrangements, also need to be identified and developed. The relevance of the information to stakeholders, and the efficacy with which it is transferred from the research arena to local communities and authorities, will dictate its ultimate influence and value to the development agenda.

In light of this analysis it is proposed that these issues be pursued through four areas of research:

1. What are the quantitative relationships between hydrological changes (including water quality) and the goods and services of aquatic ecosystems that are of high priority for food security and livelihoods?
2. What appropriate methodologies exist or need to be developed for the determination, management and monitoring of environmental flow requirements in different aquatic ecosystems?
3. What are the specific freshwater requirements for coastal ecosystems?
4. What quantity (and quality) of water is needed to sustain riverine fisheries?

What are the quantitative relationships between hydrological changes (including water quality) and the goods and services of aquatic ecosystems that are of high priority for food security and livelihoods?

Any change to the quantity of water entering an aquatic ecosystem under natural conditions will bring about changes to that system. In general, the closer to natural the desired condition of the aquatic system, the greater the portion of the original flow regime that will be required as an environmental flow. Furthermore, the pattern of flow over time (including the height, duration, smoothness, and rapidity of change of the flood, and the duration and levels of low flow) are at least as important as the total quantity of water.

In practice, relatively few aquatic ecosystems exist under natural hydrological conditions, and many are subject to highly modified flow regimes. Many of these systems continue to provide a wide range of goods and services to society, while the character of others has been altered to such an extent that previous uses are no longer sustained and serious health and other impacts have resulted. Thus, in the face of increasing competition for water, there is a critical need to be able to assess how different ecosystems respond to changes in the quantity, distribution and quality of water they receive and what portion of their natural flow they require to sustain the range of benefits that they yield. Once the relationships between river flow and one or more of the functions and benefits of an aquatic ecosystem are established, the impacts of various management strategies can be assessed, and options linking ecosystem condition (with associated goods and services) and the volume, distribution and quality of water required can be established. Such information can then be used at a local or national level to inform decisions on the allocation of water from an ecosystem in such a manner as to optimise the overall benefit to society. If long-term sustainable management of an aquatic ecosystem is intended, attention should be given to multiple aspects of ecosystem structure and functioning, as well as services, including among others maintenance of the geomorphology of river channel and floodplain, fish and bird diversity, aquatic vegetation, water quality and recreational water use.

Specific research questions in this area include:

- What are the flow-linked goods and services provided by aquatic ecosystems that are of high priority for food security and livelihoods?
- What sorts of data are required to quantify the relationship between these goods and services and different aspects of the hydrological flow regime?
- If these data do not exist in an area, how can they be collected or generated in the most cost-effective manner, and what substitute information (if any) can be used to infer the required data?
- What are the relationships between the identified goods and services and different aspects of the hydrological flow regime?
- Are there any synergistic effects, and if so what are they?

What appropriate methodologies exist or need to be developed for the determination, management and monitoring of environmental water requirements in different aquatic ecosystems?

As argued above there is limited potential for building upon experience in the North and adapting methodologies developed there to the needs of developing countries. However, there are a growing number of methodologies that have been specifically developed for, and are currently in use in developing countries. Many of these are founded on principles of aquatic ecology and advances in ecohydrology and ecohydraulics, and are fairly robust and flexible, both in their data requirements and in their output. With appropriate modification, they could also be applied more widely and in different types of aquatic ecosystems. Many of these methods, however, require an upfront decision on the desired future condition of the ecosystem under consideration and produce a single 'environmental flow requirement' (prescriptive methods, Brown and King 2002). As such, they do not lend themselves to use in situations that call for negotiation and tradeoffs between environmental and developmental issues. Others focus on the relationships between changes in river flow and one or more aspects of an ecosystem, and as such are able to provide information on different scenarios linking flow (and water quality) to ecosystem condition (interactive approaches, Brown and King 2002), and may be more appropriate for use in addressing the key research questions being addressed in the

CP. Brief descriptions of some of the methods available worldwide may be found in, *inter alia*, Tharme (1996, 2000), Dunbar et al. (1998) and Arthington and Zalucki (1998).

Environmental flow assessments are not an exact science, and the overall confidence in the results of a flow assessment for an ecosystem is a product of the extent and reliability of the data used and of the complexity of the ecosystem under consideration. In some cases the inter-linkages and complexities of aquatic ecosystems are simply too many and too great for the outcome of all potential management activities to be predicted accurately. For instance, the loss of a species or a reduction in the resilience of native aquatic communities could make way for invasions by exotic species not previously recorded in an area. Long-term changes in the climate will also have major implications for both the use and the protection of water resources. These inter-linkages and complexities are compounded by the impact of human utilisation other than water abstraction, and the impact of changes in that utilisation, can have on aquatic ecosystems. Methods need to be developed to incorporate and communicate the concept of risk—as a result both of uncertainty resulting from a paucity of information and from the inherent unpredictability of natural ecosystems—into environmental water assessments.

Specific research questions in this area include:

- What environmental flow information is most needed and/or relevant for stakeholders and decision makers in the developing world, and what is the most appropriate format for that information?
- Which of the methodologies currently available could be used, or adapted for use, in providing this information?
- What are the key features, data requirements, flow paths and outputs for any new methodologies recommended for use for providing the information required?
- How can the concepts of risk and uncertainty best be incorporated into environmental water assessments, and communicated to stakeholders and decision makers?

What are the specific water requirements for coastal ecosystems?

Methods for the assessment of flows for wetlands, groundwater and coastal systems are the least developed to date. This is partially due to the complexity and diversity of these ecosystems, but also because much of the funding for this work has been made available as part of river regulation projects. Improving understanding of, and strengthening capacity to assess, the water requirements of coastal ecosystems is particularly important given that freshwater inflow to the coast is considered by many to be "lost".

Water, nutrient and sediment inputs from rivers play an essential role in sustaining the productivity and dynamics of a wide range of coastal ecosystems. For example, subsidence and erosion as a result of reduced riverine input has been demonstrated for the Po delta and Venice lagoon in Italy, the Rhone delta in France (Hensel et al. 1999) and the Mississippi delta in the United States. The impact of such modifications in the case of tropical countries whose deltas support many millions of people such as Bangladesh, Vietnam, Mozambique or Nigeria is the subject of international concern, but has yet to be adequately quantified. Similarly, the risk of salinization in the lower reaches of river systems as well as of reduced flows at the mouth of big rivers (e.g. Vietnam, Australia) is of concern, but poorly documented and assessed. In addition to effects on agriculture, salinization creates a change in the natural vegetation structure, whose diversity is reduced, impacting subsequently on the livelihood of local populations.

The productivity of many coastal fisheries is also dependent upon freshwater inputs in a number of ways (Blaber 1997; Bunn et al. 1998). Turbid water and low salinity in estuaries act as barriers to many marine predators and so help provide safe nursery conditions. In addition, river borne nutrients fertilise inshore coastal habitats and "flood" regimes trigger the seaward migration of shrimp and the spawning of catadromous species. Some rivers floods open the temporarily closed estuaries (e.g. South and East Africa), allowing estuarine-dependant species to fulfill their biological cycle.

However, while the importance of these relationships is well understood by scientists working in the coastal zone, few of the studies carried out so far in tropical and sub-topical regions of Africa, Asia and Latin America allow quantitative analysis and clear prediction of the impacts of reduced water flow in coastal ecosystems. More such analyses are therefore required and more widely applicable predictive tools need to be developed.

Specific research questions in this area include:

- To what extent will individual coastal ecosystems be modified physically by a reduction of different levels of river flow in the estuarine zone? Does the seasonal distribution of flow significantly affect this process?
- What will be the consequences of greater salinization of the coastal zone for the livelihoods of people dependent upon coastal ecosystems and their resources?

- What what will be the impact of a reduced freshwater input on the productivity and catch composition of coastal fisheries? How does this translate into economic terms?

How much water is needed to sustain river fisheries?

River fisheries and their central role in sustaining food security and livelihoods of millions of poor people across the developing world are one of the most important benefits of natural aquatic ecosystems. Yet, for most rivers little information is available on the water management regime required to sustain fishery and its benefits in the face of increasing demand and competition for water. Therefore, there is a particularly urgent need to develop methods to assess the impact of changes in river flow regime on fish populations, fishery productivity and fishing communities; use of these methods to provide such information for selected rivers (primarily benchmark basins); and strengthen capacity of local, national and regional institutions to use these tools in making water allocation and river basin management decisions that improve food security and livelihoods of fishing dependent communities.

Welcomme and Halls (2002) have developed a generic model of tropical fishery-river flow dynamics. This is an extremely promising approach but needs to be refined further and tested on a wide range of river systems. Issues that need to be considered include: the impacts of different flow scenarios on different fish guilds, integration of more sophisticated hydrological information, more information on the population dynamics and movements of key species and the productivity of different floodplain and river habitats. The aim should be to move from the current qualitative predictions of the model to a more quantitative predictive capability.

However, equally important is the need to link such fishery-flow models with tools for environmental flow assessment. Holistic environmental flow assessment methodologies are thought to be promising for developing countries because they consider the ecosystem in its entirety and in some cases, notably downstream response to imposed flow transformations (DRIFT) (Brown and King 2000; Tharme 2000), extend the link from flow-ecosystem response through to social dependence and economic implications. However, these methodologies have only been applied in any detail in southern Africa and Australia and are still in the developmental stage. So far they have integrated only limited fisheries information and have been used on rivers with limited fisheries. Therefore, they need to be tested and expanded to incorporate recent advances in modelling of fish population dynamics and their responses to changes in river flow. Major gains can be obtained by integrating the improved Fish-Flow Model and other fish models with holistic methodologies. The value of these tools will however need to be tested in a diversity of governance situations, and effective systems of information flow established.

Specific research questions include:

- What is the relationship between various aspects of the natural hyrdological regime (notably magnitude, frequency, amplitude, duration, timing of flood and extent of inundation) and natural fish production in floodplains?
- What are the critical requirements and sensitivity to hydrological and ecological factors of the few dominant species that dominate fish catch in tropical rivers (e.g., four species make up to 50 percent of the total catch in Cambodia)?
- What are the ecological characteristics of floodplains and wetlands (both structure and processes) that are of special importance to fish, and what will be the impact of different water management options on these characteristics?
- What will be the impact of different water management options on freshwater fisheries (catch efficiency, fishing effort, shifts in fishing methods and fish catchability)?
- What are the water allocation strategies that can maximize sustainable catches of freshwater fisheries (the yield resulting from a combination of species distribution, hydro-environmental factors and fishing effort)?
- What are the water allocation strategies that can maximize the profitability of freshwater fisheries?
- What are the water allocation strategies that can maximize the positive social outcomes of freshwater fisheries?

IMPROVING WATER PRODUCTIVITY

Water productivity and the techniques used to measure it vary depending on the spatial scale being addressed—from pond/field to basin. The most widely used definition is expressed in terms of weight or value derived per unit of water used/consumed (Molden and Sakthivadivel 1999). However this is only a partial concept of water productivity. At the ecosystem or basin level water provides a wide range of goods and services, all of which need to be considered in broader analyses of the value obtained from water. Most of the previous studies of water productivity (with the notable exception of Renwick 2001) have concentrated on measuring the value of crop production only and excluded the existing and potential contributions by living aquatic resources. Therefore, there is a need not only to increase water productivity, but also to improve the methodologies for measuring water productivity.

Water productivity can be increased by producing more output per unit of water used or by reducing water losses, or by a combination of both. Various hydrological/

engineering approaches have been developed to improve water productivity by reducing water losses (Molden and Sakthivadivel 1999; Molden et al. 2001; Droogers and Kite 2001). However, in view of the analytical focus on crop productivity, it is not surprising that strategies for increasing output have so far been limited to crop cultivation only. Water productivity at several organisational levels can be increased further by integrating fish and other living aquatic resources into the existing water use systems.

In light of this analysis key questions concerning water productivity include:

1. When and how can water productivity and livelihoods be improved by integrating fish production and harvest of other aquatic animals and plants into farming and irrigation/flood-prone systems?
2. How do the monetary, social and nutritional values of these additional water-use benefits compare with those for crops?
3. What new technologies can be designed to further improve the integration of fisheries into farming systems?

When and how can water productivity and livelihoods be improved by integrating fish production and harvest of other aquatic animals and plants into farming and irrigation/flood-prone systems?

With farmers under increasing pressure to intensify and increase efficiency of resource use—including water, diversification of enterprises together with the reuse of existing on-farm resources is increasingly important. This applies for smallholder farms as well. There are numerous examples where water is managed on farms as part of normal production and survival strategies under given agroecological conditions (e.g. collection, storage, multiple use in farming—including fish ponds and flooded rice fields—and processing). Some examples of recent developments include: (i) the raised-bed farming of vegetables and fruits between a pattern of trenches used for irrigation and cultivation of fish and freshwater prawns in lowland areas of Thailand and southern Vietnam; (ii) the intensive reuse of off-farm and on-farm manures for vegetable and fish production in northern Vietnam (VAC system); and (iii) the intensified use of wetland areas (dambos) around seasonal or perennial streams for crop and (increasingly) fish production in Malawi. The latter also provides food security through the possibility of vegetable cultivation in empty ponds in drought situations, utilizing residual moisture. In places where natural aquatic ecosystems have been degraded, this integration is especially important, providing protein and other benefits that were once provided by natural systems. By becoming water managers and growers of fish and other living aquatic resources on their farms, farmers can move from being part-time fish hunters to being part-time fish farmers.

Opportunities for shared water use at the community level include irrigation schemes and seasonal floodplains. For most irrigation schemes the primary purpose for their design and establishment has been the production of agricultural crops. However, opportunities exist for fish production within the controlled waters of such schemes. These are in the water reservoir itself (usually not managed for optimal fish production), the supply canals, ponds located within the scheme area, and small trenches and pits within rice fields for combined fish-in-rice culture. In canals with constant water flow (i.e. not pulse-operated) opportunities exist for fish production in canal segments or fenced-off partitions or in net cages (if flow rates do not preclude this).

A different situation exists in flood prone ecosystems which can be used for additional fish production and thereby make use of this unutilized and free water resource. In these ecosystems where seasonal floods cover lands used for crop cultivation in the dry season, the opportunity exists to fence-in large areas (up to several hectares) by creating enclosed water bodies and stocking these with fish. In this case the communities who usually access and utilize these lands and waters can form community management groups that jointly decide on management and share of benefits, based on agreed rules. Recent work in Bangladesh and Vietnam has shown that besides the natural fish production of 200 kg/ha/ per 6 month flood period, an additional production of up to 1000 kg/ha/ per 6 month of stocked fish can be achieved (ICLARM unpublished). The arrangements involved landholders and the landless, who received shares of the returns based on their contributions to management and upkeep. The landless, who were seasonal fishers in the area, had income gains from their labor and additionally were able to conduct fishing for indigenous non-stocked fish and thereby meet their family nutritional and income requirements during this period.

Specific research questions in this area include:

- How can water productivity be measured for fisheries and aquaculture at the farm level (aquaculture)?
- When and how can on-farm water productivity be improved by integrating fish production into farming systems?
  - what tools can be developed for integrating fish production into farming systems?
  - what tools can be developed to estimate farm water productivity that will include aquatic resources?
- Where and under what conditions, can improvements to water productivity be achieved through additional and simultaneous production of fish in

various agriculture-targeted water use systems, such as irrigation schemes (i.e., reservoirs, canals, ponds, and trenches/pits in rice-fields) and seasonally flooding areas in floodplains (i.e., partially fenced-in areas)?

How do the monetary, social and nutritional values of these additional water-use benefits compare with those for crops?

Fish harvests from integrated farming systems have been shown to add significantly to the return obtained by farmers. For example in Cambodia, Guttman (1999) reports that the value of fish caught in rice fields is 37-42 percent of that of rice production. In addition, however, the culture of fish within ricefields can increase rice yields, especially on poorer soils and in unfertilized crops where the fertilizing effect of fish is greatest. In his review of trends in rice-fish farming Halwart (1998) reports that together with savings of pesticides and earnings from fish sales, these increased yields result in net incomes that are 7-65 percent higher than for rice monoculture. In more recent work the International Center for Living Aquatic Resources Management (ICLARM) has recorded a 10 percent lower cost of production for rice in flood-prone rice ecosystems in Bangladesh and Vietnam and a higher net return from rice fish of an additional US$ 400U per ha (Bangldesh), US$ 340 per ha Red river delta (Vietnam), and US$ 220 per ha in Mekong delta (Vietnam). Significantly, these benefits were obtained with no reduction in the wild fish catch. Yet while these analyses are encouraging, they are so far based on a limited number of case studies. Further analysis of a wider range of situations is therefore required.

In addition water productivity of pond aquaculture merits detailed study. For example Brummett (1997) has calculated that, even when the water requirements for feed production and pond maintenance are included, culture of channel catfish (*Ictalurus punctatus*), and tilapias (family Cichlidae) requires less water than that required to produce broiler chickens (Pimentel et al. 1997). While the figures provided by Brummett of 3350 liters of water required for each kilogram of catfish produced, and 2800 liters for each kilogram of tilapia are based on well managed ponds, and not in a practical field context, the potential is clear.

Specific research questions in this area include:

- How does the added monetary value of these additional water-use benefits compare with that for crops in terms of price per kilogram of fish, and in terms of labor and self employment for skilled and unskilled activities?
- How does fish production from these integrated systems increase the nutritional value per unit area and per unit of water used?

What new technologies can be designed to improve further the integration of fisheries into farming systems?

Despite the increasing investment in improving water use on farms, there is insufficient codification and distillation of lessons and development of new tools. As the added aquaculture enterprise will in most cases be a novel activity for the farmers, their capacity to adopt this technology and utilize the water efficiently and beneficially will depend on the quality of knowledge transfer, the existing agroecological conditions and household and farming system characteristics, as well as the social context and policy environment. For example tools need to be developed for integrating fish production into farming systems for greater water and nutrient use efficiency, and increased benefit to farm households. Specifically the comparative water use efficiency, of, for example, fish production from small farm ponds and rice fields needs to be quantified in biotechnical and economic terms, for which methods need to be developed and widely applied.

Various technical options also exist through which fish production can increase water productivity at the larger scale of irrigation systems or farming systems in flood-prone areas. Technical considerations here include environmental conditions (e.g., seasonality in temperature and bulk water supply), scheme dimensions, overall management criteria of the schemes (small-scale community managed, or large scale para-statal company operated), crops cultivated and market opportunities for the fish produced. However, experience for the combined cultivation of rice and fish in Asia, and more modest and localized experiences in Africa, underlines the importance of social, economic and institutional considerations in the design of approaches that will be taken up in the long-term at community level. As oppportunities for enhancing water productivity at the community level are pursued, there is an important need to develop a wider range of technical options that are viable under different social, economic and institutional setttings.

Specific research questions in this area include:

- What new management and operation procedures for farms, irrigation schemes (from large scale to small scale), and flood-prone areas, can be designed in a participatory manner through which the production of fish can be sustainably included as added "crop"?
- What participatory diagnostic methods and stakeholder-involving diffusion approaches will favour such approaches? Under what conditions are these effective and efficient?
- What tools can assist communities in seasonally flooding areas to establish and operate sustainable management agreements under which previously unmanaged flooded areas are utilized for fish cultivation, thereby providing tangible and equitable added benefits to all groups in the area?

Conclusions–Achieving Impact

The agenda and work described here will generate a wide range of outputs, some of the most important of which are listed in box 3. Together with a range of complementary investments in policy development, capacity building, and ultimately management of water and aquatic ecosystems using the capacity and tools generated, these outputs can have a significant long-term impact on these ecosystems, their resources, and the people who depend upon them. Amongst the most important of these impacts are:

1. Empowerment and improved engagement of poor stakeholders in the management of aquatic ecosystems and the water required to sustain these.
2. Improved livelihood opportunities, enhanced food security and improved health for these vulnerable communities.
3. Sustained production from riverine fisheries, and increased production from aquaculture.
4. Improved water productivity at farm, community and basin levels.
5. Arrested degradation of aquatic ecosystems.

Achieving these impacts will however be a complex process involving adapting the tools and approaches developed to individual situations, and negotiation and trade-offs with competing water needs. The nature of these negotiations and trade-offs will vary geographically, depending upon each country's perspectives and constraints, and with time. These processes of negotiation and trade-offs will normally seek to optimise the overall output from water resources, which in most cases will mean sub-optimal water allocations for each specific use. The work proposed here will strengthen the information base upon which such negotiations are undertaken so that the value of the resource, its water requirements, and opportunities for improving productivity are better understood. Together with, and working through, improved governance processes, the needs of different stakeholders will be better expressed and addressed. These improved negotiations will both improve the benefits from aquatic ecosystems while ensuring that they are distributed in a more equitable manner.

Policies, Institutions and Governance

- Improved understanding of the factors determining access to aquatic resources by different communities and social groups and how these can be managed

    - Guidance on the form of governance systems, policies and institutions, that foster equitable and sustainable management of aquatic ecosystems and their resources
    - Information systems that will support the development and application of such governance systems policies and institutions
    - Technical capacity to develop, manage and support such governance systems, policies and institutions

Valuation of Ecosystem Goods and Services, and the costs of Degradation

- Assessments and valuations of the goods and services provided by aquatic ecosystems, and costs of ecosystem degradation

    - Tools and methodologies for generating such information rapidly and in an accessible manner

Environmental Water Requirements

- Improved understanding of the impacts of hydrological change on the ecological functions of different aquatic ecosystems and the different goods and services they provide

    - Improved methodologies for assessment of environmental water requirements of different aquatic ecosystems
    - Improved understanding of the specific freshwater requirements of coastal ecosystems
    - Tools for assessing the water requirements of riverine fisheries

Improving Water Productivity

- Assessment of the current and potential contribution of aquatic resources to water productivity in different farming systems, notably irrigated and flood-prone systems

    - Improved understanding of the benefits that can be obtained by integrating fish production and harvest of other aquatic animals and plants into farming systems
    - Improved technologies for integrating aquaculture and fisheries into different farming systems

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