Freshwater fisheries

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12 Inland fisheries and aquaculture

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Overview

Fish and other living aquatic resources of inland water ecosystems provide important services that are seriously undervalued [well established]. Inland fisheries and aquaculture contribute about 25% to the world's production of fish. In addition, many important estuarine and coastal fisheries are strongly linked to the ecological processes that occur in freshwater systems *[well established]*. The value of freshwater production to human nutrition and incomes is much greater than gross national production figures suggest. The bulk of production is generated by small-scale activities, with exceedingly high levels of participation not only in catching and farming, but also in processing and marketing. Inland fisheries are often critical to local food security *[well established]*.

Most inland fisheries in the developing world are heavily exploited. While the fisheries are not necessarily overexploited in terms of gross production, individual species are often seriously overexploited. However, inland fisheries suffer greatly from environmental pressures, in particular deteriorating water quality and habitat *[well established]*. Many coastal and inshore marine systems are also affected by lower water quality and reduced availability of freshwater.

Competition for water and aquatic habitat is the most critical challenge facing inland fisheries in many countries [well established]. The need for water to support fish and fisheries can conflict with the needs of other sectors, in particular agriculture, in both water quality and flow requirements for sustaining aquatic habitat. Decisions on water management frequently do not take into account the impact on fish and fisheries and on the rural livelihoods of the populations that depend on them. In part this is because inland fisheries are greatly undervalued in water management at local, national, and basin levels. Equally, there is a lack of knowledge of how to optimize ecosystem services, for example, through environmental flow and water productivity approaches that are needed to guide the allocation of sufficient water to sustain fish and fisheries.

Improving the consideration of fisheries in water management decisions requires better valuation methods and improved governance [established but incomplete]. Valuations need to pay more attention to nonformal values, especially those concerning livelihoods, food security, and biodiversity. Governance systems need to incorporate such values into cross-sectoral water management that recognizes the importance of ecosystem services. Decentralization may be a possible avenue toward these governance improvements but should be planned and implemented with care if equity in access to the resource, and its full development value, is to be fostered.

There is a tradeoff between the use of water for agriculture and the provision of water in the quality and quantity required for fish production and the other goods and services generated by inland aquatic ecosystems

There are two broad challenges for fisheries production. The first is to sustain current levels of fisheries production and other ecosystem services through the provision of target-directed environmental flows that sustain or restore the aquatic environment, including its diversity *[established but incomplete]*, and improved management of capture fisheries. The second is to increase current levels of fisheries production through the wider adoption of methods for enhancing and intensifying production, such as stocking and aquaculture, that require adequate quantities of clean water, suitable habitat, and appropriate management arrangements *[established but incomplete]*. These challenges will be more successfully addressed by building partnerships between fisheries and other interest groups concerned with water management, especially those engaged in water management for agriculture, which are also searching for more efficient ways to increase the overall benefits of water productivity to food security and poverty reduction.

What inland fisheries and aquaculture contribute to economic and social development

Freshwater supplies are not only vital to river fisheries; they also sustain the fisheries of associated wetlands and influence estuarine and inshore marine fisheries.[1] Although fisheries are usually nonconsumptive users of water, they require particular quantities and seasonal timing of flows in rivers and their dependent wetlands, lakes, and estuaries. There is, therefore, a tradeoff between the use of water for agriculture and the provision of water in the quality and quantity required for fish production and the other goods and services generated by inland aquatic ecosystems (see chapter 6 on water and ecosystems).

Fisheries and aquaculture from lakes, reservoirs, rivers, ponds, and wetlands contributed about 25% (34 million metric tons) of reported world fisheries production in 2003 (FAO 2004). However, catches in rivers and associated wetlands are easy to underestimate because the contributions of numerous fisheries on smaller tributaries and water bodies are generally overlooked (Coates 2002) *[established but incomplete]*. Reported harvests from river fisheries alone have been shown to account for only some 30%–50% of actual catch (Kolding and van Zwieten forthcoming), and the contribution from inland fisheries is therefore believed to be significantly higher. In addition, the benefits of inland fisheries tend to accrue to local communities, in particular the rural poor, and their socioeconomic value is disproportionately high compared with other fisheries sectors such as high seas fisheries *[established but incomplete]*.

Despite the high productivity, water resources development planners give little recognition to freshwater-dependent fishery production or its ecological basis. Several factors contribute to this. One is the dearth of reliable data and scientific literature compared with that on industrial marine fisheries. The majority of freshwater fisheries are small-scale, spatially diffuse activities, and a significant part of the production is not commercialized or is marketed only through informal channels and is therefore not properly reflected in national economic statistics. As a consequence, these fisheries are often perceived as a low-value activity (Allan and others 2005). Aquaculture is better defined, although the reporting of fisheries that interface between enhanced natural fisheries and extensive aquaculture is less clear and makes the relative contribution of each sector difficult to assess. In addition, hydrological approaches to water management have tended to focus on in-stream quantitative flows, often ignoring the more important impacts on the quality and extent of adjacent wetlands.

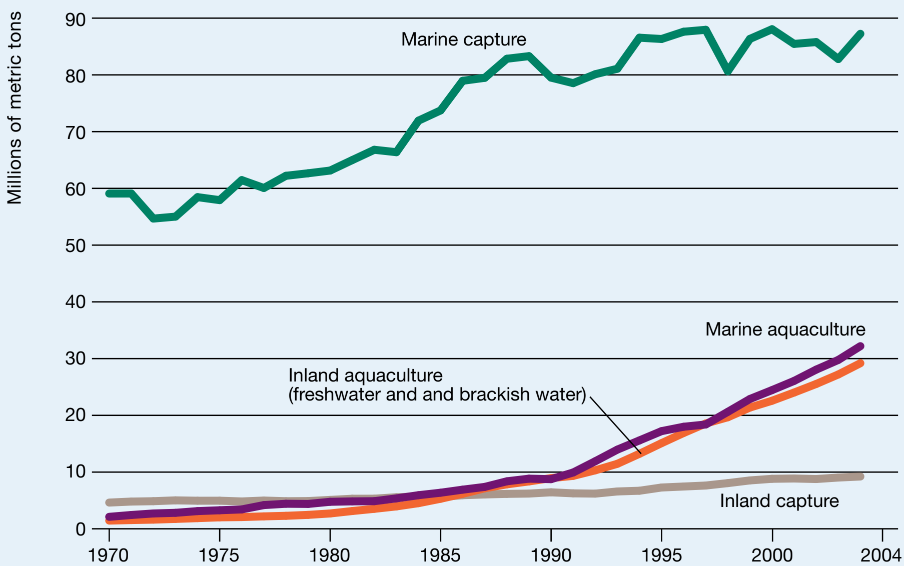
Despite the high productivity, water resources development planners give little recognition to freshwater-dependent fishery production or its ecological basis

The poor appreciation of the importance of the fishery sector has several consequences. It has exacerbated the lack of data, which has in turn hampered research and management (Misund, Kolding, and Fréon 2002) and may have biased policies and the allocation of national development resources away from fisheries. The contribution of fish to national GDP is underestimated in many countries, despite the importance to income and livelihoods. In turn, the legislative and policy frameworks for the management of inland fisheries and aquaculture development have either been absent or tended to focus on overexploitation as the primary issue when the priority need has been to improve environmental management. This impedes the role that these sectors can play at the scales of both national and local economies and in food security.

Contribution to the global economy

Fish is a highly traded commodity: roughly 33% of global fish output by value was traded across international borders in 2001 (Dey and others 2005), and it is now the fastest growing agricultural trade commodity on international markets *[well established]*. Since production remains more limited than for staple agricultural crops, and consumer demand for a healthier diet—often defined to include more fish—is increasing, the relative importance of fish is likely to continue to rise. In value terms the growth of trade in world fish products is greater than the increase in the net exports of other staple agricultural commodities such as coffee, bananas, rice, and tea (FAO 2002). In 2002 the value of world exports of fish and fish products increased to $58.2 billion—a 5% increase over 2000 (FAO 2004). At an estimated 8 million metric tons, the contribution of inland capture fisheries to total world fish production is small in comparison with marine capture fisheries and marine and inland aquaculture (figure 12.1). Nevertheless, inland fisheries have sustained annual growth of about 2% worldwide (FAO 2002), and the potential for further increases in production is high in some systems (Kolding and van Zwieten forthcoming) [*established but incomplete*].

This overall growth, however, masks the more complex reality at the regional level (figure 12.2). The main increases have been in Africa and Asia. In Africa gains reflect figure **12.1** **Though rising, inland fisheries are still a small part of total world fish production**



Source: FAO 2004.

increased yield from lakes, especially of Nile perch (*Lates niloticus*) from Lake Victoria. Production in Asia has increased for a number of reasons, notably because of the proliferation of culture-based fisheries in Bangladesh and China, but also because of improved catch statistics from the Mekong River Basin countries, among others. In contrast, declines in catches are observed in Canada and the United States, as well as in Europe, although there the economic values of recreational fisheries dominate.

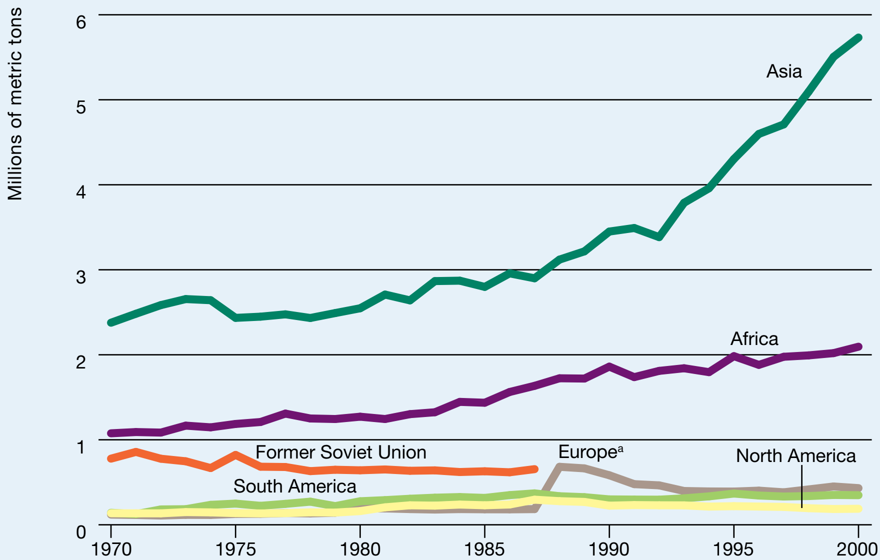
With a farmgate value of $28 billion in 2003, some three times that of inland capture fisheries, the contribution of freshwater aquaculture has increased rapidly in recent decades (FAO 2004). It is now the major contributor to inland fisheries production, having overtaken inland capture fisheries in 1986. The geographic significance of aquaculture is still uneven, with the major developments concentrated in Asia and production relatively low in Africa and some parts of Latin America.

Photo by C. Bene

Photo 12.1 In Cambodia inland fisheries play a major role in the livelihoods of millions of people

Contribution to the national economy

Inland fisheries, and related export and regional trade, can play a significant role in the economy of regions and countries. The sector contributes 7% to GDP in Cambodia (photo 12.1) and 4% in Bangladesh. In Africa inland fisheries provide employment and income for figure 12.2 **The main increases in catches from inland waters have been in Africa and Asia**



a. Includes data for the countries of the former Soviet Union from 1988 onward, including countries in Central Asia.
Source: FAO 2002.

several million people. A recent estimate of employment and income for seven major river basins finds that in West and Central Africa alone fisheries provide a livelihood to more than 227,000 full-time fishers and yield an annual catch of about 570,000 tons with a first-sale value of $295 million (table 12.1; Neiland and Béné forthcoming). The study also estimates that the total potential annual fisheries production for the region (about 1.34 million tons with an annual value of $750 million) is more than twice the estimated actual production.[2] Freshwater and brackish water aquaculture also play a major macroeconomic role in some Asian countries, notably as a source of foreign exchange and employment.

Contribution to the local economy

Where small-scale inland fisheries or aquaculture has been supported and well managed, fish-related activities play a critical role in generating wealth and sustaining economic growth (Béné 2006) [*well established*]. For example, research in the Zambezi floodplain reveals that inland fisheries generate more cash for households than cattle rearing in most cases and more than crop production in some cases (table 12.2). In Sri Lanka recent economic valuations have put the value of fisheries at about 18% of total economic returns to

table 12.1	Contribution of fisheries of the major river basins and lakes in West and Central Africa to employment and income				
		Actual production		Potential production	
River basins and lakes	**Employment** (fishers)	**Volume** (metric tons per year)	**Value** (millions of US$ per year)	**Volume** (metric tons per year)	**Value** (millions of US$ per year)
River basins					
Senegal-Gambia	25,500	30,500	16.78	112,000	61.60
Volta (rivers)	7,000	13,700	7.12	16,000	8.32
Niger-Benue	64,700	236,500	94.60	205,610	82.24
Logone-Chari	6,800	32,200	17.71	130,250	71.64
Congo-Zaire	62,000	119,500	47.80	520,000	208.00
Atlantic coastal	6,000	30,700	46.66	118,000	179.30
Lakes					
Volta	20,000	40,000	28.40	62,000	44.02
Chad	15,000	60,000	33.00	165,000	90.75
Kainji	20,000	6,000	3.30	6,000	3.30
Total	227,000	569,100	295.17	1,334,860	749.17

Note: Table excludes the numerous men and women who engage in part-time (seasonal or occasional) fishing.
Source: Neiland and Béné forthcoming.

water in irrigated paddy production (Renwick 2001). This capacity of small-scale fisheries to generate cash, however, is still poorly recognized by both academics and decisionmakers. In addition, because fishers and, to a lesser extent, fish-farmers, can access cash year-round by selling fish, fisheries provide a "bank in the water" for remote rural populations that lack access to formal financial systems. This contrasts with agriculture, where farmers have to invest and then wait for harvest before earning cash returns.

In some river basins recreational fisheries also contribute significantly to the local economy. In Europe, for instance, the inland recreational fishing industry has been valued as high as $25 billion a year (Cowx 2002). Increasing numbers of developing countries, such as Argentina, Brazil, Chile, India, and several states of the Zambezi River Basin, are also using part of their fishery resource for recreational fisheries to boost their local tourist economy.

Contribution to gender empowerment

The water sector is often presented as a key entry point for poverty alleviation and gender empowerment (see chapter 4 on water and poverty). While professional fish capture (harvesting) is dominated by men, post-harvest activities (fish processing, fish retailing, and trading) are often done by women, in particular in Africa but also in many other parts of the world (photo 12.2) [*well established*]. Uneducated and poor women are often involved in post-harvest activities, which do not require large capital investments or high technical skills. A large proportion of small-scale (household) fishers are women and children. Some may be so successful in running their fish trade that they become owners of boats or outboard engines or are able to provide loans to fishers to purchase fishing equipment.

table 12.2	Contribution of fisheries and other activities to households' cash income in different parts of the Zambezi River Basin (U.S. dollars per household per year)							
	Barotse floodplain		Caprivi-Chobe wetlands		Lower Shire wetlands		Zambezi Delta	
Activity	**Value**	**Share** (%)	**Value**	**Share** (%)	**Value**	**Share** (%)	**Value**	**Share** (%)
Cattle	120	28	422	37	31	7	0	..
Crops	91	22	219	19	298	66	121	48
Fish	180	43	324	28	56	12	100	39
Wild animals	6	1	49	4	1	..	0.4	..
Wild plants	24	6	121	11	48	11	29	11
Wild foods	0	..	11	1	7	2	4	2
Clay[a]	2	..	0	..	8	2	0.1	..

.. Less than one.
a. For pots and other utensils.
Source: Turpie and others 1999.

For millions of other women, however, fish processing and trade are more about economic survival. They often operate in an informal environment, making their contributions less visible than those of the rest of the sector. For these women, the income generated by post-harvest activities is often their only source of cash income, in particular in societies where men control a large part of the household's main cash-generating activities *[established but incomplete]*. Studies have shown that a disproportionately high number of vulnerable women, such as female heads of households, are involved in post-harvest fishery activities, which then play a crucial safety-net function.

These fish-related activities represent a vital element of the day to day struggle for economic and social empowerment. That struggle is often exacerbated by the fact that women are rarely recognized as legitimate stakeholders in the sector and the management

Photo by C Bene

Photo 12.2 Fish trade can contribute to the economic empowerment of women process, and their specific needs and aspirations are not systematically integrated into the design of fisheries and aquaculture policies and management.

Aquaculture

Aquaculture is the farming of fish and other aquatic organisms and contributes directly to increasing the productivity of water. Aquaculture consists of a flexible and adaptable set of technologies, species, and systems ranging from simple ponds receiving no inputs and infrequent stocking to massive, high-technology cage or raceway systems that can produce up to 100 kilograms (kg) per cubic meter of fish. Many of these systems are relevant to the needs and contexts of developing countries and water-stressed countries (table 12.3).

Aquaculture contributes directly to increasing the productivity of water

Most aquaculture is conducted in earthen ponds, but at a wide range of intensities. At the low end are small ponds of less than 500 square meters, which contribute to the stability and durability of small-scale farming systems in Asia, Africa, and Latin America. When regularly stocked and fertilized, these units produce 1,000–2,000 kg per hectare per year of fish for household consumption and sale or barter. Even on this scale aquaculture has been shown to substantially improve the economic and biophysical functioning of farms (Dey and others 2006).

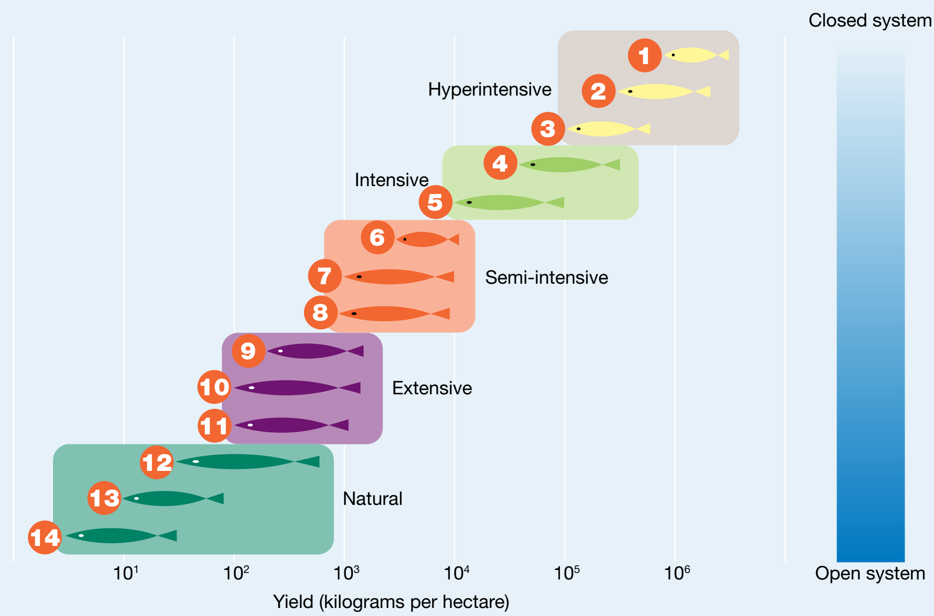
At the higher end of the pond aquaculture spectrum are intensive systems that use mechanical aeration and pelleted feeds to overcome natural constraints to productivity. When the necessary inputs (feeds, fingerlings, fuel, electricity, spare parts) and infrastructure (roads, markets) are available, these systems regularly produce more than 10,000 kg per hectare per year and proportionally large returns to investment (figure 12.3). However, overloading ecosystems in this way decreases the sustainability of other ecosystem services. Catastrophic disease problems have been known to devastate the industry, as occurred in Asian penaeid shrimp farming in the 1990s. Destruction of mangroves for pond

table **12.3** **Productivity from aquaculture systems in developing countries**

Production system	Production volume (kilograms per hectare)
Tilapia, unfertilized ponds (Diana 1997)	320
Red Swamp Crayfish, extensive rice paddies (Arringnon and others 1994)	750
Malaysian prawn, fed ponds (Lake Harvest Aquaculture, Ltd. 2003)	2,500
Tilapia, fertilized ponds (Diana 1997)	3,200
Tilapia, fed ponds (Diana 1997)	5,900
Tilapia, intensive ponds (Diana 1997)	10,000
Indian carp polyculture (Murthy 2002)	13,600
Clarias, flow-through ponds (Hatch and Hanson 1992)	40,000
Tilapia, fed cages (Arringnon and others 1994)	500,000
Common carp, intensive cages (Akiyama 1991)	1,100,000
Clarias, flow-through tanks (Hatch and Hanson 1992)	8,500,000

figure 12.3 Production from different capture and culture systems varies greatly

1 Recirculation systems
2 Raceways
3 Cages
4 Completely fed and aerated ponds
5 Fertilized and fed ponds
6 Brush parks and pens
7 Fertilized ponds
8 Heavily stocked, fertilized ponds
9 Extensive stocked unfertilized ponds
10 Drain-in ponds
11 Extensively stocked natural systems
12 Tropical lakes and rivers
13 Temperate lakes and rivers
14 Cold temperate lakes and rivers



Source: Adapted from Welcomme and Bartley 1998.

construction, although now curtailed in most places, has also had serious negative social and economic effects on rural communities (Primavera 1997).Between these two extremes lie a wide variety of productive and sustainable fish culture systems. Ponds can produce 3,000–5,000 kg per hectare per year on agricultural by-products such as brewery waste, oilseed cakes, brans, and manures and can add value to processing while transforming low-value products into high-value animal protein. Fish are cold blooded and neutrally buoyant, so they do not waste energy on keeping warm or resisting gravity, making them more energy efficient to grow than other animals.

Integrated agriculture-aquaculture—taking advantage of economic synergies

Aquaculture probably began in Asia as a modification of an existing farming system to include fish (Beveridge and Little 2002). Many farmers who do not consider themselves aquaculturists stock fish into reservoirs or livestock watering ponds for mosquito and weed control, but benefit additionally through recreational fishing and improved household food security. Rice farmers in Asia have traditionally managed the aquatic fauna of paddy fields as a valuable supplement to rice production. Examples of integrated agriculture-aquaculture systems are now found throughout the world. The basic principles are to use the nutrients found in agricultural by-products for fish production and to optimize the agricultural use of water. Fish production has been successfully integrated into row crops (especially rice), hydroponic horticultural systems, silkworm production, and animal husbandry (pigs, poultry, rabbits, small ruminants, cattle).

> As with other agricultural diversification strategies, integrated agriculture and aquaculture also reduce risks to vulnerable, often rain-fed, small-scale farming systems

Driving integrated agriculture-aquaculture systems are the economic synergies to be had by amortizing capital and labor investments over a wider range of production units. Although these systems are knowledge intensive, overall costs for inputs, weed control, and waste disposal are reduced while profits are enhanced *[well established]*. As with other agricultural diversification strategies (intercropping, crop rotations), integrated agriculture and aquaculture also reduce risks to vulnerable, often rain-fed, small-scale farming systems by adding a production module that:

- Does not require daily feeding (fish may not grow, but will not normally regress with irregular feeding).
- Requires minimal labor (less than 10% of that needed for crops and 30% of that needed for other types of animal husbandry).
- Holds water for emergency use by the household or other production units.
- Produces a high-value crop that can be eaten by the family or sold.

A widespread type of integrated agriculture and aquaculture is the integration of fish into rice paddies. As most rice is grown in standing water, a certain number of fish are always present in the system, although this has been reduced in some areas by the need to use pesticides and herbicides with high yielding systems. Typically, "natural" rice paddies produce 120–300 kg per hectare per year of diverse mixed fish and other animals that contribute directly to household diets and in some cases to profit margins. More intensively managed fish stocking and harvesting have been shown to increase rice yields (through weed control and soil aeration) by some 10% while producing up to 1,500 kg per hectare of fish and reducing both the need for pesticides and the cost (dela Cruz 1994; Halwart and Gupta 2004).

Photo by R. Welcomme

Photo 12.3 Rice-fish integrated culture in Bangladesh

China (3.3 million hectares) and India (2.5 million hectares) have the largest areas under rice-fish cultivation, followed by Indonesia, Malaysia, Thailand, and Viet Nam. The community-based management of fisheries, aquaculture, and rice farming practiced in Bangladesh (photo 12.3) and Sri Lanka is a good example of how to achieve maximum synergy through appropriate technical and management interventions (Dey and Prein 2003). Fish production on these floodplains has increased from the traditional 50–70 kg per hectare to 650–1700 kg per hectare, while maintaining rice production at 6–7 metric tons per hectare.

Aquatic invertebrates, including mosquito larvae, form a major part of the food chain in rice paddy ecosystems, and fish predation on these has been shown to reduce the incidence of malaria and possibly other diseases (Nalim 1994).

Cage aquaculture—flexible, but experiencing setbacks

Tilapia, carp, catfish, and a number of other species are produced in cages (Beveridge 2004). Provided that water currents are sufficient to disperse metabolic wastes from the cages, production can be adapted to the overall carrying capacity of the river, lake, or reservoir in which they are situated to prevent excessive environmental change. Sustainable production per cycle in such systems is typically in the range of 10–50 kg per cubic meter, depending on the natural productivity of the water, the ability of the ecosystem to absorb wastes, and other uses for the water, such as for drinking. The fish in these systems must be fed more or less complete diets, meaning that substantial inputs of nutrients to natural waters are sometimes unavoidable, which can increase the risk of surface water pollution and eutrophication. On the other hand, in irrigated systems the introduction of caged fish and their feeds, by increasing nutrient concentrations, can reduce fertilizer costs and increase yields of the irrigated crops (Beveridge and Muir 1999).

Cage culture technology can increase the overall production of valuable table fish and mitigate the effects of environmental changes. It also has social advantages in that landless people can find habitation and employment in cage aquaculture (Costa Pierce 2002). Small-scale cage aquaculture has been shown to be a flexible technology adaptable to the needs of poor people, as in Bangladesh. By placing only the cages and their contents under the ownership of the landless, cage aquaculture is not reliant on ownership or leasing of land or a water body and promotes the use of otherwise "fallow" water bodies (Hambrey, Beveridge, and McAndrew 2001). Operations carried out over shorter periods, such as fish over-wintering, nursing, and fattening in small cages, fit well with the income-generating strategies of the poor by providing them with a potential source of income in periods of hardship and shortage (McAndrew, Little, and Beveridge 2000).

Cage culture technology can increase the production of valuable table fish, mitigate the effects of environmental changes, and provide habitation and employment for landless people

There are also a number of associated industries such as cage construction, feed supply, and transport of products that can serve as a nucleus for the development of whole regions, as happened with the Chilean salmon industry. When integrated in ponds, cage culture allows the simultaneous farming of fish species at different trophic levels (caged fish are fed high-protein diets, while open-pond filter feeding species depend on caged-fish wastes), enabling incremental production of biomass per unit of water while recycling nutrients (Yang and Lin 2000).

Cage culture has suffered setbacks, however, as conflicts with other users and environmental externalities (pollution) have arisen, prompting planners to adopt a more integrated approach (Beveridge and Muir 1999). It has proved difficult to estimate environmental capacity or to implement environmental management plans, resulting in overexploitation of lake environments, with occasional fish kills and economic hardship for those involved (Beveridge 2004; Abery and others 2005). A further problem has been the guarantee of access rights for landless poor people who can benefit from cage technology once it has proved economically viable. There are also fears that placing cages in canals might reduce water currents, thereby increasing deposition of solids and increasing canal maintenance costs. As a result, cage farming in irrigation canals is prohibited in some countries.

Water use in aquaculture—wide variability in requirements

Surprisingly, fish production uses no more water—and in many cases much less—than the production of other animal foods (Phillips, Beveridge, and Clarke 1991; Brummett 1997, 2006; Verdegem, Bosma, and Verreth 2006) and, for the case of rain-fed systems, the periodicity of water supply is also much less critical for fish than for crops such as maize. However, care must be taken in comparing water consumption by various types of aquaculture and livestock and crops (table 12.4). Data come from different sources and cover a considerable period of time, and assumptions are often unstated.

Although aquaculture has tended to become more efficient in use of water, it is nonetheless highly variable, with water use for intensive aquaculture generally being higher where there are no incentives to reduce use. Water use includes both consumptive use (losses in pond systems associated with seepage and evaporation) and nonconsumptive

table **12.4** **Water requirements for various types of aquaculture**

Food crop/production system	**Water requirement** (metric tons per cubic meter)	**Relative importance of nonconsumptive water losses in aquaculture**
Potatoes	500	
Wheat	900	
Sorghum	1,110	
Corn (maize)	1,400	
Rice	1,912	
Soybeans	2,000	
Broiler chickens	3,500	
Beef	100,000	
Clarias; intensive, static ponds	50–200	Low to medium
Tilapia; extensive, static ponds	3,000–5,000	Medium to high
Tilapia; sewage, minimal exchange ponds	1,500–2,000	Medium to high
Tilapia; intensive, aerated ponds	21,000	Low to medium
Carp/tilapia polyculture; conventional ponds	12,000	Medium to high
Carp/tilapia polyculture; semi-intensive ponds	5,000	Low to medium
Carp/tilapia polyculture; intensive ponds	2,250	Low to medium
Carp; intensive raceways	740,000	Low
Channel catfish; intensive ponds	3,000–6,000	Low to medium
Trout; raceways	63,000–252,000	Low
Salmonids; ponds/tanks	252,000	Low to medium
Salmonids; cages	2,260,000	None
Penaeid shrimp; semi-intensive ponds	11,000–21,430	Low to medium
Penaeid shrimp; intensive ponds	29,000–43,000	Low
Penaeid shrimp; intensive raceways	55,125	Low

Source: Philipps, Beveridge, and Clarke 1991; Piemental and others 1997; Brummett 2006.

use (water that passes through the aquaculture system and is returned to the river or lake from which it was taken with little need for treatment). Unlike the case in agriculture, nonconsumptive losses can be high in aquaculture. Data in table 12.4 also do not include indirect water use associated with aquaculture feeds (see Brummett 2006 and Verdegem, Bosma, and Verreth 2006 for discussions). (For more detailed consideration of water use in agriculture, readers should consult the appropriate chapters in this volume.) Note too that there are various ways to express water consumption: water use per unit of biomass production or per unit of protein or in energy production terms (see Brummett 2006 for discussion).

Keeping water flowing

Freshwater fish resources are probably among the most resilient harvestable natural resources, provided their habitat, including the quantity, timing, and variability of river flow, is maintained (Welcomme and Petr 2004) *[well established]*. Their management and conservation can be approached only at the ecosystem level (figure 12.4), as changes in flow and water quality in rivers and river-dependent water bodies can have major impacts on fisheries production there and downstream. These changes may arise naturally, due to climatic variability, as in Sahelian rivers (Dansoko, Breman, and Daget 1976; Lae and others 2004). More commonly, they result from human modifications to the flow regime and the functioning of the ecosystem, in particular from reduced extent and duration of flooding that undermine biological production and reduce the potential for fisheries *[well established]*.

Many species of fish and other aquatic organisms are sensitive to variations in the timing, quantity, quality, and temperature of water

Rivers and associated wetlands—maintaining environmental flows

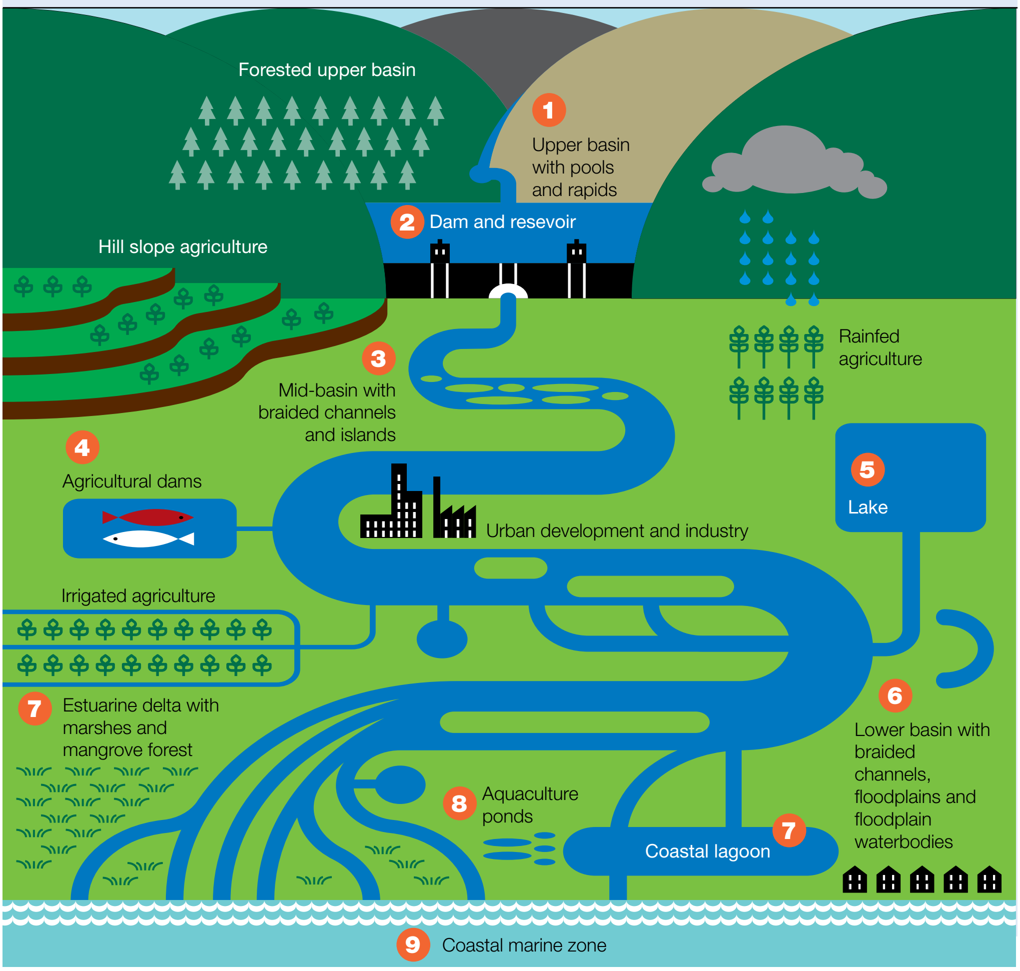
Reduced flows in main river channels lead to significant changes, in particular reductions in area of associated wetlands (floodplains and floodplain swamps and lakes). This results in net production losses through direct habitat loss. The direct conversion of wetlands to agricultural use has similar consequences.

Many species of fish and other aquatic organisms are sensitive to variations in the timing, quantity, quality, and temperature of water, which are important, for example, as essential triggers to migration and breeding *[well established]*. Different fish species generally use different parts of the aquatic system, including the main channels of rivers, seasonally attached wetlands, lakes and reservoirs, and estuaries and near-shore marine areas. Some species use all or many of these areas and need to migrate between them. All these areas have to be treated as a continuum. Different species have different flow needs, and most species react negatively to changes in the hydrograph (Bunn and Arthington 2002).

Changes to river morphology due to altered flows may interfere with the connectivity and channel diversity that are essential for the survival of many species (Dollar 2004). Other changes include silting or removal of critical substrates that act as spawning sites for many species and a source of invertebrate food for others (Arthington and others 2004). Where water quality is poor, reduced flows increase the risk of deoxygenation and other effects of contamination. Hydrological conditions that fall outside the range of natural variation in rivers may cause the fauna to become simplified, with the replacement of

figure 12.4 | **Schematic view of a river basin showing ecological zones and their role in fisheries and some activities that interact with water use**

1 Many species of fish are specialized for life in the upper basins of rivers. Other species from downriver migrate to upriver sites to spawn.
2 Dams heavily affect downstream fish fauna but also create opportunities for new fisheries. Where native species are not well adapted to lake conditions, new species may need to be introduced.
3 Mid-basin braided reaches often have specialized faunas adapted to the rapidly changing and unpredictable hydrological conditions found there.
4 Agricultural dams provide an opportunity for fisheries as a parallel crop, usually by stocking.
5 Lakes have specialized fauna adapted to still water conditions and support valuable fisheries.
6 Floodplains are essential habitats for many species of fish that migrate onto them during floods to reproduce and feed. Floodplain water bodies and rice fields also support distinctive fauna.
7 Estuarine areas and coastal lagoons are among the most productive fisheries. They depend on a specific balance of fresh and marine waters.
8 Aquaculture ponds can occur throughout the river basin associated with aquaculture or on their own.
9 Inland coastal and near-shore marine areas are influenced by inflows of freshwater, silt, and nutrients and by the access to upstream areas for migratory species.



larger species by less valuable small generalists or introduced species, and may lead to the elimination of migratory and other sensitive species and a general loss of biodiversity (Welcomme 1999). Maintaining environmental flows must therefore include sustaining ecosystem service provision as well as sustaining broader ecosystem connectivity and functioning for conserving biodiversity.

Lakes and reservoirs—a dependence on river flows

All reservoirs and most lakes depend on flow from rivers for their productivity or their very existence. Year to year fluctuations in the productivity of Lake Kariba (Zambia and Zimbabwe) and Lake Turkana (Kenya) illustrate the dependence of even large water bodies on river inflows, which provide both variation in area and inflow of nutrients (Karenge and Kolding 1995; Kolding 1992). Other lakes, such as Lake Chilwa (Malawi) and Lake Chad (Cameroon, Chad, Niger, and Nigeria), depend on inflow for their existence—a reduction or failure in flooding from inflowing rivers results in diminished area and failure of their fisheries, although these are restored when more normal flow conditions reappear (van Zwieten and Njaya 2003). In the Aral Sea water abstractions in support of irrigated agriculture for non-food crops led to the loss of about 50,000 metric tons of food fish per year (Petr 2004).

All reservoirs and most lakes depend on flow from rivers for their productivity or their very existence. Coastal fisheries are also vulnerable to changes in freshwater inputs

The productivity of reservoirs and dams can be influenced by filling, drawdown, and abstraction regimes. Abrupt changes in water level can be detrimental to certain species. For example, tilapia species, which are commonly present in reservoirs and lakes, nest on the shallow bottom, and rapid changes in level may submerge or expose the nests, resulting in breeding failure (Amarasinghe and Upasena 1985; De Silva 1985; De Silva and Sirisena 1988) *[established but incomplete]*.

Marine and brackish water areas—vulnerability to changes in freshwater inputs

Coastal fisheries are also vulnerable to changes in freshwater inputs. For example, the pelagic fisheries of the eastern Mediterranean experienced a marked downturn following the regulation of the Nile River's flow by the Aswan High Dam (Nixon 2004). There is also evidence that coral reefs and their fish populations can be affected when freshwater discharge patterns are modified *[established but incomplete]*, particularly where land use results in excessive sedimentation. In fresh-salt water transitional zones in estuaries, changes to flow can affect the intrusion of salt water into the freshwater system and associated soils (photo 12.4). This affects not only the distribution, reproduction, larval development, and growth of many freshwater, brackish water, and marine fish, crustacea, and molluscs but also the suitability of land for agriculture. Mangrove forests are particularly at risk in areas where coastal transition zones suffer changes in salinity by reductions in freshwater inputs or are degraded by declining sediment deposition.

Aquaculture—reliance on consistent inputs of clean water

Many forms of aquaculture are viable only if flow conditions are suitable. Successful rearing of fish generally depends on reliable supplies of clean water, although many rain-fed stillwater ponds and more advanced recirculation systems may be extremely economical

In fresh-salt water transitional zones in estuaries, changes to flow can affect the intrusion of salt water into the freshwater system and associated soils

Photo by C. Bene

Photo 12.4 Shrimp aquaculture can greatly affect soil quality by increasing salinity

of water use. Intensive running water culture systems need constant inputs of high quality water to ensure sufficient oxygen for the fish and removal of wastes; sufficient flow is needed in rivers into which farm effluents are discharged to dilute wastes and nutrients without damaging ecosystems (Brown and King 1996). In many parts of the world certain flow criteria must be met before farm licenses are granted, and alterations to flow can place farms in jeopardy.

Water management—an ecosystem approach is crucial

The ecosystem approach to managing watersheds, with the rivers, wetlands, lakes, estuarine areas, and land viewed as part of a continuum, is fundamental to managing water for inland fisheries. This approach should consider not only water quantity and quality but also the connectivity of the system because many species of fish must be able to move between spawning, nursery, and feeding areas within a basin. This management approach needs to consider land use practices, such as agriculture and forestry, as well as the needs of industry, urban areas, and waterborne transport that affect basin processes and the quality, quantity, and timing of flows. The approach is further complicated by the fact that many river basins are transboundary and may be located within several countries, necessitating international mechanisms to regulate and manage river flows.

Evaluating the amount of water needed in the system

The negative impact of alterations in flows means that efforts have to be made to maintain the flow in rivers and other flow-sensitive systems if fisheries are to be sustained. This flow is termed an environmental flow and, for fishery purposes, is defined as that portion of the original flow of a river that is needed to maintain specific valued features of its ecosystem or the quantity of water that must be maintained in a river system at all times to protect the species of interest for fisheries or for conservation of the environments on which they depend (Arthington and others forthcoming). The provision of environmental flows is not intended to mimic a pristine river but rather to support the ecological functioning of the river to sustain its desired services to people and nature.

A range of methods has been developed to determine the environmental flow requirements for rivers, wetlands, and estuaries (Tharme 2003; Arthington and others forthcoming), but most are used only in small rivers in temperate zones. Methods are beginning to be developed and used for large systems as well, but they are still incomplete (Tharme 2003).

Environmental flows are an important tool for assessing ecological requirements for water. The desired environmental flow for a river depends on the management objective. The environmental flow for sustaining biota is not the same as that for optimal ecosystem service provision, for example. If developed and applied properly, measures of environmental flow have considerable potential to improve the technical basis of tradeoff decisions for water allocation.

Damming has proved particularly detrimental to downstream fisheries by suppressing flood peaks and preventing the periodic inundations of floodplains downstream, altering their timing and preventing instream migration

The type of environmental flow regulation needed to maintain fisheries depends on the primary cause of flow modification and the desired nature of the fishery. Restrictive management is required where water is abstracted directly from a donor waterbody. Licenses to abstract water should be granted only when sufficient water will remain in the system to guarantee flows that allow the fish and fisheries to function at desired levels, including during periods of low flow. Active management is required where releases from dams are involved. Artificial flow regimes are needed to create peak flows timed to act as triggers for breeding and to provide water of sufficient depth and duration to flood riparian wetlands long enough for young fish to grow. The flows should also allow fish to migrate, access riparian floodplains, and otherwise complete their normal life cycles. Active management can also be applied to poldered systems, where the floodplain is enclosed to control flow for rice and other crops. Correct management of the sluices controlling flow can favor fish as well as rice (Halls 2005) *[established but incomplete]*.

Impact of water management schemes

Damming for power generation, flood control, and urban supply and leveeing and poldering to control flooding for urban development and agriculture all affect flow regimes and habitat availability, which in turn can affect the contributions of fish and fisheries to water productivity *[well established]*. Damming has proved particularly detrimental to downstream fisheries (World Commission on Dams 2000) by suppressing flood peaks and preventing the periodic inundations of floodplains downstream, altering their timing and preventing instream migration (Bunn and Arthington 2002), with negative consequences for fishing communities. The growing trend in Bangladesh of enclosing lowland floodplains with polders, for example, is denying many species of migratory fishes access to large areas of floodplain. Cross-basin transfers may be particularly damaging as they rob one river, whose fauna is degraded as a consequence, to discharge the water into another system, where the new hydrograph may exceed the capacity of the fauna to deal with it *[speculative]*, and transfer alien species or genotypes from one system to the other.

The volume of water removed for irrigated agriculture can also harm downstream fisheries. Irrigation accounts for some 70% of all water removed from rivers (gross abstraction).[3] Although some of this water may be returned to the donor river, the discharged water may be of lower quality and the timing may be inappropriate. The net impact of these high levels of removal on fisheries has rarely been investigated, although it is assumed from knowledge of the dynamics of fish populations in rivers that such effects are generally deleterious *[established but incomplete]*. However, in some irrigated landscapes such as rice farming systems, aggregated impacts of irrigation on fisheries production and on the livelihoods of fishing communities are not always negative at the catchment level, as demonstrated in Lao PDR and Sri Lanka (Nguyen-Khoa, Smith, and Lorenzen 2005b). Further investigation of such impacts is urgently needed.

> Environmental economics theory has made tremendous progress in incorporating the nonmarket goods and services provided by ecosystems into economic frameworks and decisionmaking; still needed are approaches to resource valuation that quantify less tangible social functions and services

Realizing the opportunities

The chapter has highlighted the value of inland fisheries and aquaculture and the opportunities for improving water productivity. The chapter also identified several constraints that need to be overcome. To ensure optimal benefits, appropriate mechanisms for evaluation, decisionmaking, and governance regarding fisheries and aquaculture need to be fully incorporated into water allocation processes.

Improving evaluation of fisheries

There is an urgent need for more holistic evaluation techniques that take into account the different contributions of fisheries to water productivity. Environmental economics theory has made tremendous progress in incorporating the nonmarket goods and services provided by ecosystems into economic frameworks and decisionmaking—for example, the development and implementation of valuation techniques and concepts such as total economic value, existence or option values, and contingency valuation (see, for example, Barbier 1989 and Willis and Corkindale 1995). Still needed, however, are approaches to resource valuation that quantify less tangible social functions and services, such as food security, provision of financial safety nets, and the spreading of risk, a need that is particularly acute for fisheries. Where better valuation has occurred, the profile of fisheries has been raised and national policies on water allocation to support fisheries have been adjusted accordingly.

These new evaluation techniques need to draw on innovative approaches that attempt to include community perceptions of these different social services and functions through an integrated participatory assessment (Nguyen-Khoa, Smith, and Lorenzen 2005a). The challenge is to internalize these overlooked benefits, collectively for all services provided by water including fisheries, into a new interpretation of water productivity.

Accommodating new investment approaches

The private sector is increasingly involved in the economic development of fisheries and aquaculture, in particular at the micro-level. This is illustrated by the exponential increase in private sector-led aquaculture farming in Asia and Latin America. Private investment in fisheries and aquaculture is driven by several factors. The increasing demand of urban markets for fish is turning the focus of inland fisheries away from rural subsistence, and this is driving changes in fisheries practice and in the social and economic orientation of many fisheries. This tends to favor the intensification of production systems, leading eventually to monoculture. Securing a return on investment is accompanied by increasing control over resources (including fish habitat) by individuals or limited groups.

Privatization of the common-pool resource is a form of enclosure of the commons. This can have tremendous negative impacts on vulnerable socioeconomic groups (usually the poorest, with a large number of women), which rely more heavily on these resources to sustain their livelihoods through subsistence harvesting, generally under informal communal access rights. In Asia this enclosure has already occurred following the aquaculture boom and the development of enhanced fisheries in oxbows and ponds (Ahmed and others 1998). It is now taking place in Africa through the privatization of the large lakes in Eastern and Southern Africa (for example, Lake Kariba and Lake Malawi) by commercial cage culture ventures and by brush park fisheries in West Africa.

An increasing number of governments and development organizations are promoting institutional frameworks that draw on private sector dynamism, while allowing a certain degree of pro-poor growth and limiting the risks of exclusion

Export-oriented policies have also been a major catalyst for private investors to develop commercial, high-value, large-scale fish production systems. These new export-oriented commercial strategies raise concerns about local food security and livelihood equity, including for a large number of women (Abila 2003).

The processing sector is also being transformed by greater vertical integration and sophistication and intensification of the processing technologies in response to more stringent international food quality standards (such as Hazard Analysis Critical Control Point certification, or HACCP). This trend is accompanied by growing consumer demand for environmental and, increasingly, social, standards for production. Certification or labeling requirements may deny or reduce access to international or even national markets to small-scale producers. These producers may, however, continue to supply local consumers, thereby slowing the current trend in declining domestic fish availability observed in certain developing countries.

An increasing number of governments and development organizations are promoting institutional frameworks that draw on private sector dynamism, while at the same time allowing a certain degree of pro-poor growth and limiting the risks of exclusion. Public-private partnership has been identified as one potential option in this search for pro-poor growth.

Improving governance

A broader policy and improved governance environment is needed to stimulate pro-poor growth, including through adequate support to investment and public-private partnerships that optimize the benefits of fisheries. These should ensure high levels of participation in decisionmaking by all stakeholder groups, including fishery interests at all levels (photo 12.5). Such an improved governance environment should create and enforce mechanisms to ensure the accountability of the different public and private actors whose actions affect the allocation of water and water productivity, including that reflected through fisheries.

Effective governance of aquatic resources is rare, especially in developing countries. Most governments and institutions have failed to design governance mechanisms and policy processes that account for the aspirations and needs of the rural populations that depend on inland aquatic resources for their livelihoods. In an effort to address this weakness, an increasing number of governance reforms have been launched since the early 1990s.

Most governments and institutions have failed to design governance mechanisms and policy processes that account for the aspirations and needs of the rural populations that depend on inland aquatic resources for their livelihoods


Photo by R. Welcomme

Photo 12.5 Improving water governance is critical to the participation of all stakeholders in the decisionmaking process

Decentralization and participatory democratization, in particular, are seen as necessary to improve governance mechanisms. Reforms are often associated with improvements in public accountability, environmental sustainability, and empowerment of poor and vulnerable groups. Decentralization is perceived as a possible means of improving rural livelihoods and reducing poverty (World Bank 2000; IFAD 2001).

The most common argument is that decentralization is by definition a mechanism for inclusion and empowerment because it involves bringing government closer to the governed, making government more knowledgeable about, and hence more responsive to, the needs of the poorest and most marginalized people, including women, who are rarely recognized as legitimate stakeholders. This mechanism of inclusion is expected to lead to greater empowerment and stronger pro-poor policies and outcomes. In fisheries, community-based management and comanagement arrangements are now frequently promoted successfully as part of this governance reform (Pomeroy 2001; Berkes and others 2001).

Recent reviews suggest, however, that decentralization reforms raise a number of challenges for natural resources management, particularly water use (Dupar and Badenoch 2002; Ribot 2002). The decentralized level provides little opportunity to address issues of transboundary resources, including water and shared and migratory fish stocks. It is more difficult to create the managerial conditions and knowledge necessary to integrate the water flow requirements of fisheries into watershed or basinwide integrated water resource management. The level of coordination and information necessary for a sustainable and equitable allocation of water between the different users across a basin is rarely achieved.

Many proposed reforms contravene legislation in many countries, particularly on access to fisheries and land and water tenure. Decentralization reforms need to embrace legislative reform to support the rights and responsibilities of local communities to stewardship of resources and to provide capacity building for both resource users and decentralized officers. Improved information flows, lower transaction costs, and clearly defined goals and responsibilities of government units at all levels will be necessary to deal in an integrated way with complex and potentially conflicting resource management issues emerging at basin, national, and international levels (Brugere 2006).

Decentralization should not be seen as a universal panacea to improve equity and empowerment. As empirical evidence demonstrates, when human capacity and social capital at the community level are low, decentralization may exacerbate unequal power distribution and reinforce the marginalization of some groups because elite groups capture decisionmaking mechanisms (Abraham and Platteau 2000; Béné and Neiland 2006). As a result, policy decisions at the local level still frequently favor powerful groups such as large landowners (through irrigation schemes and water user associations, for example) or even large herd owners, to the detriment of the vast majority of society, especially fisher groups (Ratner 2003).

An essential attribute of an effective inland fishery policy framework is an ecosystem approach to fisheries, which includes fisheries considerations and related environmental concerns in integrated planning, particularly for water use

Developing an intersectoral policy framework adapted to inland fisheries

The consensus among practitioners and scholars is clearly that new evaluation techniques, investment approaches, and governance reforms can support and improve the contribution of fisheries and aquaculture to water productivity. Implementation of these approaches still represents an enormous challenge for a large number of institutions in developing countries, however. Adaptive policy support mechanisms are required to ensure that reforms realize the potential local economic development and improved food security benefits. Many countries lack a wider integrated natural resource management framework into which inland fisheries can fit. Effective policies for the conservation and sustainable use of freshwater biodiversity are also generally absent despite the increased recognition of its role.

Many countries have yet to develop national policy and legal frameworks tailored to inland fisheries. More commonly, inland fisheries continue to be placed under policy frameworks that evolved to address coastal and marine fisheries. There is an urgent need for all countries to develop and implement frameworks specific to inland fisheries. These should have explicit links to integrated approaches to sustaining aquatic environments.

An essential attribute of an effective inland fishery policy framework is an ecosystem approach to fisheries, which includes fisheries considerations and related environmental concerns in integrated planning, particularly for water use. This is still a major challenge in the low-capacity and data-deficient environment in developing countries. However, an ecosystem approach offers a much better adapted framework for fishery management than the sector-based approach still prevalent in most developing countries. One mechanism to promote such integrated, multisectoral approaches is participatory scenario-based negotiations, which can better integrate the needs of stakeholder groups within fisheries with those of other interests and take account of gender perspectives. These processes should facilitate the establishment of intersectoral consensus mechanisms through collective negotiation of land and water issues and consideration of their relationship to aquaculture and fisheries.

Reviewers

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Notes

1. The word *fishery* includes finfish, crustaceans, molluscs, and other miscellaneous animals but excludes the harvest of plants.

2. Potential production is calculated using standard coefficients relating the surface of water bodies (river or floodplain) to potential production rates (metric tons per hectare per year) as typically observed for these water bodies and classically used in the literature (see, for example, Welcomme 2001).

3. See www.fao.org/ag/agl/aglw/aquastat/water_use/index6.stm.

References

Abery, N.W., F. Sukadi, A.A. Budhiman, E.S. Karamihardja, S. Koeshendrajana, and S.S. De Silva. 2005. "Fisheries and Cage Culture of Three Reservoirs in West Java: A Case Study of Ambitious Development and Resulting Interactions." *Fisheries Management and Ecology* 12 (5): 315–30.

Abila, R.O. 2003. "Fish Trade and Food Security: Are They Reconcilable in Lake Victoria?" In *Report of the Expert Consultation on International Fish Trade and Food Security. Casablanca, Morocco, 27–30 January.* FAO Fisheries Report 708. Rome: Food and Agriculture Organization.

Abraham, A., and J.-P. Platteau. 2000. "The Central Dilemma of Decentralized Rural Development." Conference on New Institutional Theory, Institutional Reform, and Poverty Reduction, London School of Economics, 7–8 September, London.

Ahmed, I., S.R. Bland, C.R. Price, and R. Kershaw. 1998. "Open Water Stocking in Bangladesh: Experiences from the Third Fisheries Project." In Tomi Petr, ed., *Inland Fishery Enhancements*. FAO Fisheries Technical Paper 374. Rome: Food and Agriculture Organization and UK Department for International Development.

Akiyama, D.M. 1991. "The Use of Soybean Meal Based Feeds for High Density Cage Culture of Common Carp in Indonesia and the People's Republic of China." ASA Technical Bulletin AQ 28-1991. American Soybean Association, Singapore.

Allan, JD., R. Abell, Z. Hogan, C. Revenga, B.W. Taylor, R.L. Welcomme, and K. Winemiller. 2005. "Overfishing of Inland Waters." *Bioscience* 55 (12): 1041–51

Amarasinghe, U.S., and T. Upasena. 1985. "Morphometry of a Man-made Lake in Sri Lanka: A Factor Influencing Recruitment to Cichlid Fishery." *Journal of the National Aquatic Resources Agency* 32: 121–29.

Arrignon, J.C.V., J.V. Huner, P.J. Laurent, J.M. Griessinger, D. Lacroix, P. Gondouin, and M. Autrand. 1994. *Warm-water Crustaceans*. Netherlands: Technical Centre for Agriculture and Rural Cooperation.

Arthington, A.H., R. Tharme, S.O. Brizga, B.J. Pusey, and M.J. Kennard. 2004. "Environmental Flow Assessment with Emphasis on Holistic Methodologies." In R. Welcomme and T. Petr, eds., *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries Volume II*. Food and Agriculture Organization, Regional Office for Asia and the Pacific, Bangkok.

Arthington, A.H., E. Baran, C.A. Brown, P. Dugan, A.S. Halls, J.M. King, C.V. Minte-Vera, R.E. Tharme, and R.L. Welcomme. Forthcoming. "Water Requirements of Floodplain Rivers and Fisheries: Existing Decision-Support Tools and Pathways for Development." Comprehensive Assessment of Water Management in Agriculture Research Report 17. International Water Management Institute, Colombo.

Barbier, E. 1989. "The Economic Value of Ecosystems: Tropical Wetlands." Briefing papers on key issues in environmental economics. LEEC Gatekeeper 89–92. International Institute for Environment and Development, London.

Béné, C. 2006. "Small-scale Fisheries: Assessing Their Contribution to Rural Livelihoods in Developing Countries." FAO Fisheries Circular 1008. Food and Agriculture Organization, Rome.

Béné, C., and A.E. Neiland. 2006. *From Participation to Governance: A Critical Review of the Concepts of Governance, Co-management, and Participation and Their Implementation in Small-scale Inland Fisheries in Developing Countries.* Penang, Malaysia, and Colombo: WorldFish Center and Consultative Group on International Agricultural Research Challenge Program on Water and Food.

Berkes, F., R. Mahon, P. McConney, R. Pollnac, and R. Pomeroy. 2001. *Managing Small-scale Fisheries: Alternative Directions and Methods*. Ottawa: International Development Research Center.

Beveridge, M.C.M. 2004. *Cage Aquacul ture*, 3rd ed. Oxford: Blackwell Publishing.

Beveridge, M.C.M., and D.C. Little. 2002. "Aquaculture in Traditional Societies." In B.A. Costa-Pierce, ed., *Ecological Aquaculture*. Oxford: Blackwell Publishing.

Beveridge, M.C.M., and J. F. Muir. 1999. "Environmental Impacts and Sustainability of Cage Culture in Southeast Asian Lakes and Reservoirs." In W.L.T. van Densen and M.J. Morris, eds., *Fish and Fisheries of Lakes and Reservoirs in Southeast Asia and Africa*. Otley, UK: Westbury Publishing.

Brown, C.A., and J.M. King. 1996. "The Effects of Trout-farm Effluent on Benthic Invertebrate Community Structure in South-western Cape Rivers." *South African Journal of Aquatic Science* 21 (91/2): 3–21.

Brugere, C. 2006. "Can Integrated Coastal Management Solve Agriculture-Fisheries-Aquaculture Conflicts at the Land-Water Interface? A Perspective from New Institutional Economics." In C.T. Huong, T.P. Tuong, J.W. Gowing, and B. Hardy, eds., *Environment and Livelihoods in Coastal Tropical Zones: Managing Agriculture-Fishery-Aquaculture Conflicts*. Wallingford, UK: CABI Publishing.

Brummett, R. E. 1997. "Farming Fish to Save Water." *Bioscience* 47 (7): 402.

———. 2006. "Comparative Analysis of the Environmental Costs of Fish Farming and Crop Production in Arid Areas: A Materials Flow Analysis." Paper presented to the International Workshop on the Environmental Costs of Aquaculture, April 25–28, Vancouver, Canada.

Bunn, S.E., and A.H. Arthington. 2002. "Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity." *Environmental Management* 30 (4): 492–507.

Coates, D. 2002. *Inland Capture Fishery Statistics of Southeast Asia: Current Status and Information Needs*. RAP Publication 2002/11. Food and Agriculture Organization, Regional Office for Asia and the Pacific, Asia-Pacific Fishery Commission, Bangkok.

Costa Pierce, B.A. 2002. "Sustainability of Cage Aquaculture Ecosystems for Large-scale Resettlement from Hydropower Dams: An Indonesian Case Study." In B.A. Costa-Pierce, ed., *Ecological Aquaculture*: *The Evolution of the Blue Revolution*. Oxford: Blackwell Publishing.

Cowx, I.G. 2002. "Recreational Fishing." In P.J.B. Hart and J.D. Reynolds, eds., *Handbook of Fish Biology and Fisheries*. Oxford: Blackwell Publishing.

Dansoko, D.D., H. Breman, and J. Daget. 1976. "Influence de la secheresse sur les populations d*'hydrocynus* dans le delta centrale du Niger." *Cahier ORSTOM (Hydrobiol)* 10 (2): 71–76.

dela Cruz, C.R., ed. 1994. *Role of Fish in Enhancing Ricefield Ecology and in Integrated Pest Management*. International Center for Living Aquatic Resources Management Conference Proceedings 43. WorldFish Center, Penang, Malaysia.

De Silva, S.S. 1985. "Observations on the Abundance of the Exotic Cichlid *Sarotherodon mossambicus* (Peters) in Relation to Fluctuations in the Water-level in a Man-made Lake in Sri Lanka." *Aquaculture and Fisheries Management* 16: 265–72.

De Silva, S.S., and H.K.G. Sirisena. 1988. "Observations on the Nesting Habits of *Oreochromis mossambicus* (Peters) (Pisces: Cichlidae) in Sri Lankan Reservoirs." *Journal of Fish Biology* 33 (5): 689–96.

Dey, M.M., and M. Prein. 2003. "Participatory Research at Landscape Level: Flood-prone Ecosystems in Bangladesh and Vietnam." In B. Pound, S.S. Snapp, C. McDougall, and A. Braun, eds., *Managing Natural Resources for Sustainable Livelihoods: Uniting Science and Participation.* London and Ottawa: Earthscan and International Development Research Centre.

Dey, M.M., P. Kambewa, M. Prein, D. Jamu, and F.J. Paraguas. 2006. "Impact of the Development and Dissemination of Integrated Aquaculture-Agriculture (IAA) Technologies in Malawi." In D. Zilberman and H. Waibel, eds., *The Impact of NRM Research in the CGIAR.* Wallingford, UK: CABI Publishing.

Dey M.M., M.A. Rab, A. Kumar, A. Nisapa, and M. Ahmed. 2005. "Food Safety Standard and Regulatory Measures: Implications for Selected Fish Exporting Asian Countries." *Aquaculture Economics and Management* 9 (1–2): 217–36.

Diana, J. 1997. "Feeding Strategies." In H.S. Egna and C.E. Boyd, eds., *Dynamics of Pond Aquaculture*. Boca Raton, La.: CRC Press.

Dollar, E.S.J. 2004. "Fluvial Geomorphology." *Progress in Physical Geography* 28 (3): 405–50.

Dupar, Mari, and Nathan Badenoch. 2002. *Environment, Livelihoods, and Local Institutions—Decentralization in Mainland Southeast Asia*. Washington, D.C.: World Resources Institute.

FAO (Food and Agriculture Organization). 2002. *The State of World Fisheries and Aquaculture*. Fisheries Department. Rome.

———. 2004. *The State of World Fisheries and Aquaculture*. Fisheries Department. Rome.
Halls, A.S. 2005. "The Use of Sluice Gates for Stock Enhancement and Diversification of Livelihoods." Project R8210. Fisheries Management Science Programme. Marine Resources Assessment Group, London.
Halwart, M., and M.V. Gupta, eds. 2004. *Culture of Fish in Rice Fields.* Penang, Malaysia: Food and Agriculture Organization and the WorldFish Center.
Hambrey, J., M. Beveridge, and K. McAndrew. 2001. "Aquaculture and Poverty Alleviation 1. Cage Culture in Freshwater in Bangladesh." *World Aquaculture* 32 (1): 50–55, 67.
Hatch, L.U., and T.R. Hanson. 1992. "Economic Viability of Farm Diversification through Tropical Freshwater Aquaculture in Less Developed Countries." International Center for Aquaculture, Auburn University, Ala.
IFAD (International Fund for Agricultural Development). 2001. *Rural Poverty Report 2001: The Challenge of Ending Rural Poverty.* Oxford: Oxford University Press.
Karenge, L.P., and J. Kolding. 1995. "On the Relationship between Hydrology and Fisheries in Man-made Lake Kariba, Central Africa." *Fisheries Research* 22 (3): 205–26.
Kolding, J. 1992. "A Summary of Lake Turkana: An Ever-changing Mixed Environment." *Mitteilungen-Internationale Vereinigung für Theoretische und Angewandte Limnologie* 23: 25–35.
Kolding, J., and P.A.M van Zwieten. Forthcoming. "Improving Productivity in Tropical Lakes and Reservoirs." Consultative Group on International Agricultural Research Challenge Program on Water and Food, Bergen, Norway.
Lae, R., S. Williams, A. Malam Massou, P. Morand, and O. Mikolasek. 2004. "Review of the Present State of the Environment, Fish Stocks and Fisheries of the River Niger (West Africa)." In R. Welcomme and T. Petr, eds., *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries* Vol. I. RAP Publication 2004/16. Bangkok: Food and Agriculture Organization, Regional Office for Asia and the Pacific.
Lake Harvest Aquaculture, Ltd. 2003. "Key Production Parameters." Zimbabwe.
McAndrew, K.I., D. Little, and M.C.M. Beveridge. 2000. "Entry Points and Low Risk Strategies Appropriate for the Resources Poor to Participate in Cage Aquaculture: Experiences from CARE-CAGES Project, Bangladesh." In I.C. Liao and C. Kwei Lin, eds., *Cage Aquaculture in Asia: Proceedings of the First International Symposium on Cage Aquaculture in Asia.* Manila and Bangkok: Asian Fisheries Society and World Aquaculture Society, Asia Branch.
Misund, O.A., J. Kolding, and P. Fréon. 2002. "Fish Capture Devices in Industrial and Artisanal Fisheries and their Influence on Management." In P.J.B. Hart and J.D. Reynolds, eds., *Handbook of Fish Biology and Fisheries*. Vol. II. London: Blackwell Publishing.
Murthy, H.S. 2002. "Culture and Feeding of Indian Major Carps." American Soybean Association, New Delhi.
Nalim, S. 1994. "The Impact of Fish in Enhancing Ricefield Ecosystems." In C.R. dela Cruz, ed., *Role of Fish in Enhancing Ricefield Ecology and in Integrated Pest Management*. International Center for Living Aquatic Resources Management Conference Proceedings 43. WorldFish Center, Penang, Malaysia.
Neiland, A., and C. Béné, eds. Forthcoming. "Tropical River Fisheries Valuation: A Global Synthesis and Critical Review." WorldFish Center and International Water Management Institute, Penang, Malaysia and Colombo.
Nguyen Khoa, S., L. Smith, and K. Lorenzen. 2005a. "Adaptive, Participatory and Integrated Assessment (APIA) of the Impacts of Irrigation on Fisheries: Evaluation of the Approach in Sri Lanka." Working Paper 89. International Water Management Institute, Colombo.
———. 2005b. "Impacts of Irrigation on Inland Fisheries: Appraisals in Laos and Sri Lanka." Comprehensive Assessment of Water Management in Agriculture Research Report 7. Comprehensive Assessment Secretariat, Colombo.
Nixon, S.W. 2004. "The Artificial Nile." *American Scientist* 92 (2): 158–65.
Petr, T. 2004. "Irrigation Systems and their Fisheries in the Aral Sea Basin, Central Asia." In R.L. Welcomme and T. Petr, eds., *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries.* Vol. I. RAP Publication 2004/16. Bangkok: Food and Agriculture Organization, Regional Office for Asia and the Pacific.
Phillips, M.J., M.C.M. Beveridge, and R.M. Clarke. 1991. "Impact of Aquaculture on Water Resources." In D.R. Brune and J.R. Tomasso, eds., *Aquaculture and Water Quality*. Advances in World Aquaculture Series. Vol. 3. Baton Rouge, La.: World Aquaculture Society.
Piemental, D., J. Houser, E. Preiss, O. White, H. Fang, L. Mesnick, T. Barsky, S. Tariche, J. Schreck, and S. Alpert. 1997. "Water Resources: Agriculture, the Environment and Society." *Bioscience* 47 (2): 97–106.
Pomeroy, R. 2001. "Devolution and Fisheries Co-management." In R. Meinzen-Dick, A. Knox, and M. Di Gregorio, eds., *Collective Action, Property Rights and Devolution of Natural Resource Management: Exchange of Knowledge and Implications for Policy*. Feldafing, Germany: Deutsche Stiftung für Internationale Entwicklung/Zentralstelle für Ernährung und Landwirtschaft (DSE/ZEL).
Primavera, J.H. 1997. "Socio-economic Impacts of Shrimp Culture." *Aquaculture Research* 28 (10): 815–27.

Ratner, B. 2003. "The Politics of Regional Governance in the Mekong River Basin." *Global Change* 15 (1): 59–76.
Renwick, M.E. 2001. *Valuing Water in Irrigated Agriculture and Reservoir Fisheries: A Multiple-use Irrigation System in Sri Lanka*. Research Report 51. Colombo: International Water Management Institute.
Ribot, Jesse. 2002. *Democratic Decentralization of Natural Resources: Institutionalizing Popular Participation*. Washington, D.C.: World Resources Institute.
Tharme, R.E. 2003. "A Global Perspective on Environmental Flow Assessment: Emerging Trends in the Development and Application of Environmental Flow Methodologies for Rivers." *River Research and Applications* 19 (5-6): 397–441.
van Zwieten, P.A.M, and F. Njaya. 2003. "Environmental Variability, Effort Development and the Regenerative Capacity of the Fish Stock in Lake Chilwa, Malawi." In E. Jul-Larsen, J. Kolding, J.R. Nielsen, R. Overa, and P.A.M. van Zwieten, eds., *Management, Co-management or No Management? Major Dilemmas in Southern African Freshwater Fisheries.* Part 2: Case Studies. FAO Fisheries Technical Paper 426/2. Rome: Food and Agriculture Organization.
Verdegem, M.C.J., R.H. Bosma, and J.A.V. Verreth. 2006. "Reducing Water Use for Animal Production through Aquaculture." *Water Resources Development* 22 (1): 101–13.
Welcomme, R.L. 1999. "A Review of a Model for Qualitative Evaluation of Exploitation Levels in Multi-species Fisheries." *Journal of Fisheries Ecology and Management* 6 (1): 1–20.
Welcomme, R.L., and D.M. Bartley. 1998. "An Evaluation of Present Techniques for the Enhancement of Fisheries." *Journal of Fisheries Ecology and Management* 5: 351–82.
Welcomme, R.L., and T. Petr, eds. 2004. *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries Volume I.* RAP Publication 2004/16/17. Bangkok: Food and Agriculture Organization, Regional Office for Asia and the Pacific.
Willis, K.G., and J.T. Corkindale, eds. 1995. *Environmental Valuation, New Perspectives.* Wallingford, UK: CABI Publishing.
World Bank. 2000. *World Development Report 2000/2001: Attacking Poverty.* New York: Oxford University Press.
World Commission on Dams. 2000. *Dams and Development: A New Framework for Decision-making.* Report of the Word Commission on Dams. London: Earthscan.
Yang, Y., and C.K. Lin. 2000. "Integrated Cage Culture in Ponds: Concepts, Practices and Perspectives." In I. C. Liao and C. Kwei Lin, eds., *Cage Aquaculture in Asia. Proceedings of the First International Symposium on Cage Aquaculture in Asia.* Manila and Bangkok: Asian Fisheries Society and World Aquaculture Society, Asia Branch.