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Lost in Development's Shadow: The Downstream Human Consequences of Dams

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ABSTRACT: The World Commission on Dams (WCD) report documented a number of social and environmental problems observed in dam development projects. The WCD gave particular emphasis to the challenges of properly resettling populations physically displaced by dams, and estimated the total number of people directly displaced at 40-80 million. Less attention has been given, however, to populations living downstream of dams whose livelihoods have been affected by dam-induced alterations of river flows. By substantially changing natural flow patterns and blocking movements of fish and other animals, large dams can severely disrupt natural riverine production systems – especially fisheries, flood-recession agriculture and dry-season grazing. We offer here the first global estimate of the number of river-dependent people potentially affected by dam-induced changes in river flows and other ecosystem conditions. Our conservative estimate of 472 million river-dependent people living downstream of large dams along impacted river reaches lends urgency to the need for more comprehensive assessments of dam costs and benefits, as well as to the social inequities between dam beneficiaries and those potentially disadvantaged by dam projects. We conclude with three key steps in dam development processes that could substantially alleviate the damaging downstream impacts of dams.

KEYWORDS: Dams, rivers, dam-affected people, inland fisheries, flood-plain agriculture, food security, poverty alleviation, water resources development, hydropower, environmental flows, ecosystem services

INTRODUCTION

Large dams became a prominent instrument for economic development in the past century. Worldwide, the number of large dams stood at 5000 in 1950 (ICOLD, 1998); three quarters of these were in North America, Europe, and other industrial regions. By 2000, the number of large dams had climbed to over 45,000, and these were spread among more than 140 countries (ICOLD, 1998). On average, two large dams were built per day for half a century (WCD, 2000). Today, the number of large dams exceeds 50,000 (Berga et al., 2006).

These dams provide water storage that has enabled large cities like Phoenix, Arizona, to grow in desert regions. They supply hydropower that has electrified many rapidly expanding industrial and urban economies, from Seattle to Shanghai. Large dams are also important in agriculture. About half of the world's large dams were built primarily for irrigation, many of them in Asia as the Green Revolution spread (WCD, 2000). Today large dams are estimated to contribute directly to 12-16% of global food production (WCD, 2000). Undeniably, large dams have played an important role in economic development.

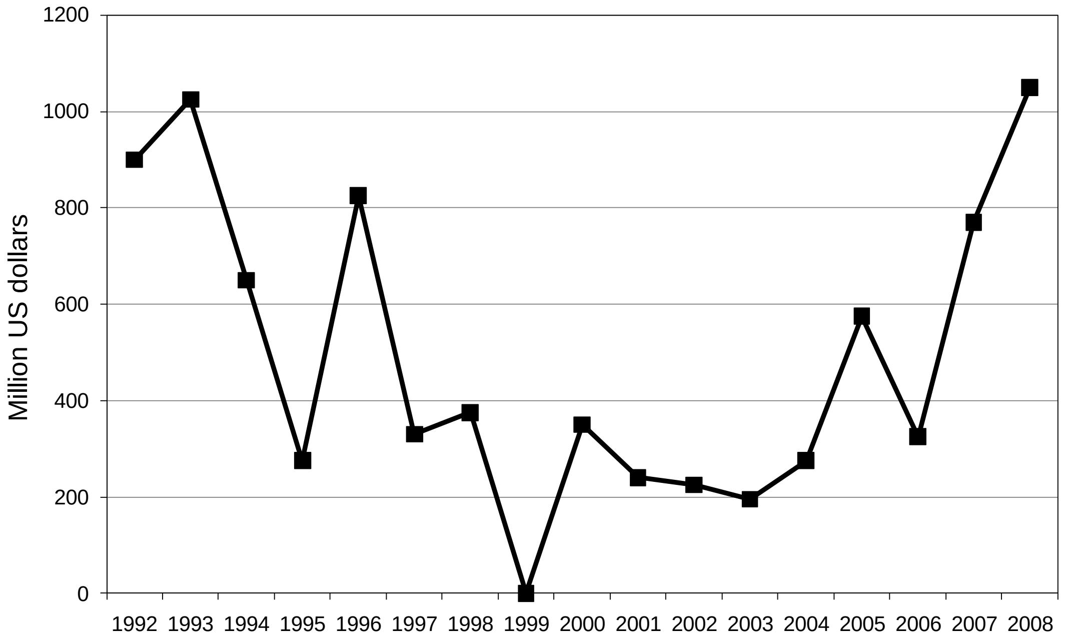
However, large dams have also brought serious environmental and social consequences. Whereas the benefits have generally been delivered to urban centres or industrial-scale agricultural developments, river-dependent populations located downstream of dams have commonly experienced a difficult upheaval of their livelihoods, loss of food security, and other impacts to their physical, cultural and spiritual well-being. River flows altered by large dams often disrupt or destroy downstream habitats and life cycle cues for fish and other river species, as well as fishing, cropping and grazing systems that rely on flood-plain ecosystems. While downstream river-dependent communities may benefit from some degree of flood protection and enhanced irrigation opportunities provided by dams, adverse impacts are far more common and usually outweigh the benefits to downstream people, resulting in reduction of their incomes and livelihoods.

The nature, duration and severity of these impacts vary from one dammed river to another. In some of the cases documented in this study, the wave of social disruption and human health impacts following dam construction largely passed within a decade, but in other cases dam-induced impacts have persisted through multiple generations. In some cases, impacts may be mitigated by alternative sources of food or employment; in other cases, they may not. And in some cases, the environmental effects of dams are detectable for only a short distance downstream, while in others those effects remain significant through hundreds of river kilometres. What the majority of cases have in common, however, is the failure to account for these impacts and their consequences on downstream populations.

In its ground-breaking 2000 report, the World Commission on Dams (WCD) brought much-needed global visibility and media attention to the benefits and costs of large dams. But while the WCD Report documented the downstream impacts of dams for a number of case examples, much of the report's discussion of social impacts focused on the physical displacement of populations living in the immediate vicinity of dam construction. The WCD estimated that 40-80 million people had been displaced by large dams. However, no estimate was provided of the downstream populations impacted by the alterations in river flows and freshwater ecosystems that accompanied these development projects.

Fresh attention to these downstream dam impacts is overdue and urgently needed. The timing of the WCD Report marked the low-point of a decade-long decline in dam financing, driven in large part by effective and persistent protests against large dams by social and environmental NGOs and affected river communities. However, dam construction is again on the rise. Coincident with the WCD Report, the new millennium brought new reports on the dire and worsening condition of the world's poor, and rapidly accumulating evidence that intense droughts and floods due to climate change could make prospects for poverty alleviation ever-more challenging. Private and state companies and development banks have increased their involvement in financing and building large new dams to provide drinking water, irrigation, and hydroelectricity supplies (figure 1). Hydropower dams are emphasised as a source not just of electricity but also of funds to finance other development options such as irrigation.

Figure 1. Global investment in dams dropped precipitously in the 1990s, but has risen sharply since (adapted from World Bank Group, 2009).



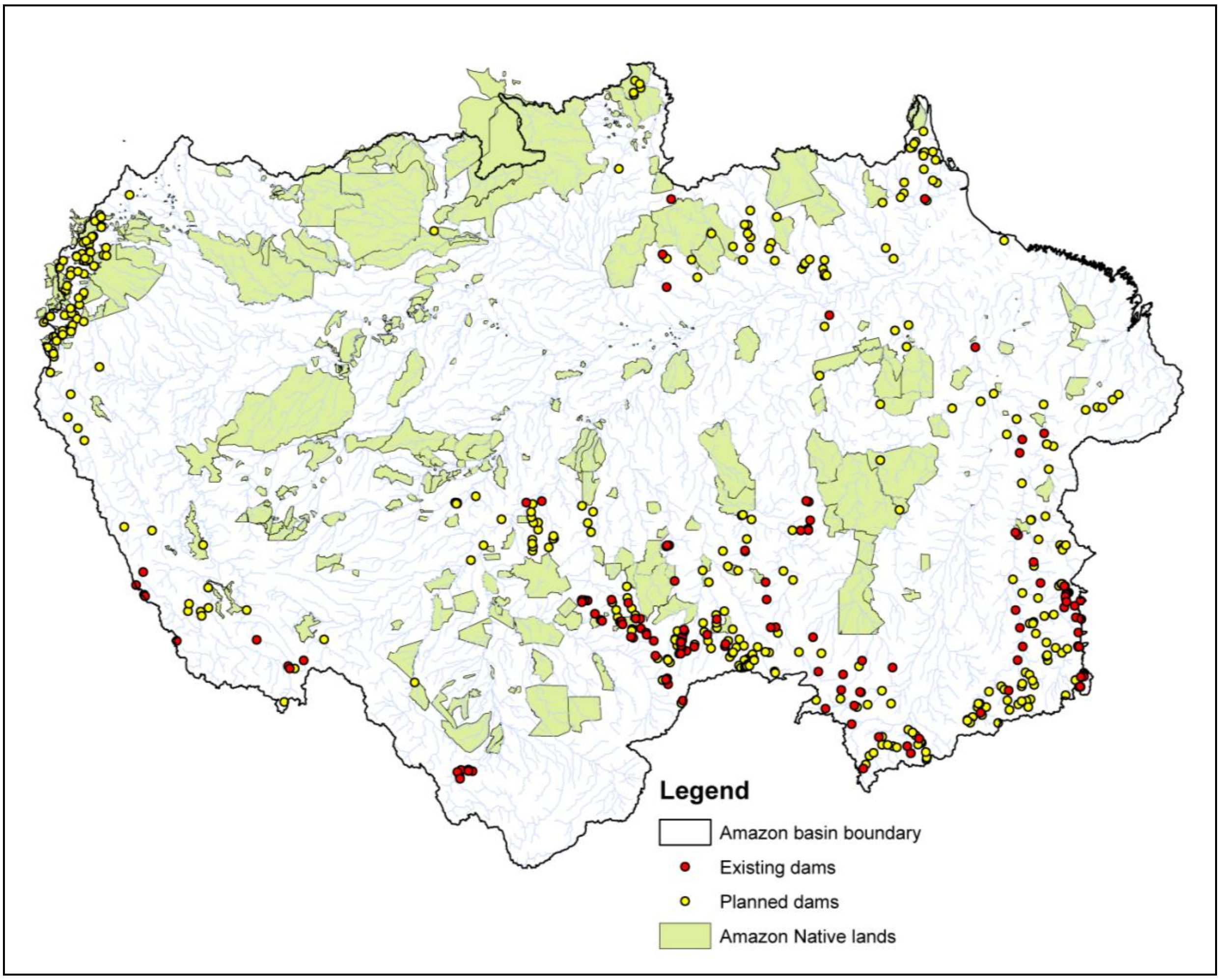
The majority of the thousands of new large and small dams are under construction or on the drawing boards are in the developing world and in fast-growing economies with rising demands for additional hydroelectricity. In South America, for example, at least 2200 large dams are planned or under construction, including 1700 in Brazil alone, where the potential for additional environmental impacts and social disruption associated with new dams is quite high (figure 2).[1] Clearly, a more complete assessment of the downstream impacts of dam development is urgently needed to inform ongoing and future dam development plans.

In this paper, we attempt to begin filling this gap. In addition to providing further elaboration of the consequences of dams on downstream populations, we offer the first global estimate of the number of downstream riparian dwellers potentially affected by the largest ~7000 dams built to date. By 'potentially affected' we mean those rural riparian populations that are prone – due to their physical vicinity and likely dependence – to experience negative effects on their livelihoods by altered river flows, such as through reduced food security or the loss of ecosystem goods and services. Our identification of potentially affected people is based upon their proximity to dammed rivers (i.e. within 10 km), the exposure of the landscape (i.e. river deltas and slopes < 1 degree are presumed to sustain fisheries and flood-plain agriculture), and the degree of flow regulation that a river experiences. Our conservative estimate of 472 million suggests that the number of people potentially affected downstream of large dams exceeds by six to 12 times the number directly displaced by these structures (previously estimated at 40-80 million; WCD, 2000). In the process of developing this new global

[1] Estimates of the number of dams planned or under construction come from multiple sources compiled by The Nature Conservancy. For South America, important sources include the following: http://sigel.aneel.gov.br/brasil/viewer.htm (Brazil); www.conelec.gov.ec/ (Ecuador); http://energia.mecon.ar/proyectoshidroelectricos/buscarproyecto.asp (Argentina); Ministerio de Energia y Minas, Dirección General de Electricidad – DGE (Peru).

estimate, we have compiled a literature database documenting dam effects on people living along more than 120 rivers in at least 70 countries.

Figure 2. Existing and planned dams, and federally designated indigenous reserves in the Amazon river basin (Dam location source: Ministerio de Minas e Energia, Brazil).



Our conclusion is that dam development projects aimed at reducing poverty or improving economic opportunities are benefitting many but are also deepening poverty and hunger for others. The failure to adequately account for these impacts precludes an honest rendering of the net costs and benefits of dams. In this paper we document the fact that a sizeable proportion of the human population is being fed by the natural productivity of river ecosystems. A central premise of this paper is that it does not make sense to continue to damage these natural life-support systems when far-less destructive approaches to dam development are readily available, as detailed later in this paper. The world's governments cannot hope to achieve poverty alleviation targets, including the Millennium Development Goal of halving the proportion of people who suffer from extreme hunger and poverty by 2015 (United Nations, 2008), if new and existing dam projects continue to impoverish millions of river-dependent people.

HUMAN DEPENDENCE ON RIVERS

Societies need and value rivers for a host of reasons – from the spiritual and aesthetic to the cultural and very practical. Rivers provide water to drink, to irrigate crops, and to generate electric power that benefits, in one way or another, just about everyone on earth. But there is a segment of the human population that depends very directly on aspects of the river ecosystem that are sustained by particular patterns of river flow – the highs and lows, floods and droughts – that a river exhibits in its relatively natural state (table 1). Just as species evolve in response to variable environmental conditions, human cultures have evolved and adapted to the availability of resources and services provided by natural ecosystems. For those populations that continue to be closely dependent on river ecosystems, disruptions in flow by a dam can mean a disruption in the freshwater goods and services that sustain them – especially fish, flood-recession crops, and flood-plain vegetation used for grazing. In Cambodia, for example, about 60% of the population's protein comes from fish derived from the Mekong's Tonle Sap, a unique and highly productive freshwater ecosystem now threatened by dam construction upstream (Smith et al., 2005). It is estimated that some 60-70 million people in the lower Mekong basin rely upon fish as their primary source of protein (Mekong River Commission, 2005; Baran et al., 2007).

Large dams affect downstream river-dependent communities in myriad ways. The most common and most threatening impact is the loss of food security that stems from changes in the flow regime – especially the loss of seasonal flooding (see figure 3 for an illustration from the Zambezi river). Seasonal floods hydraulically connect a river with the surrounding landscape, promoting the exchange of water, nutrients and organisms among a rich mosaic of habitats. This river-flood-plain connection increases both species-diversity and biological productivity. The moist, naturally fertilised flood-plain soils also allow for sustainable cropping systems that provide food during the drier months. Herders also look to flood-plains for water and grazing areas for their livestock during the dry season. Without the influx of water and nutrients in this annual cycle of flooding, these flood-plain production systems can disappear, taking with them human livelihoods.

Figure 3. Changes in river flow patterns following construction of Cahora Bassa dam in 1974 on the Zambezi river in Mozambique (from Beilfuss and dos Santos, 2001).

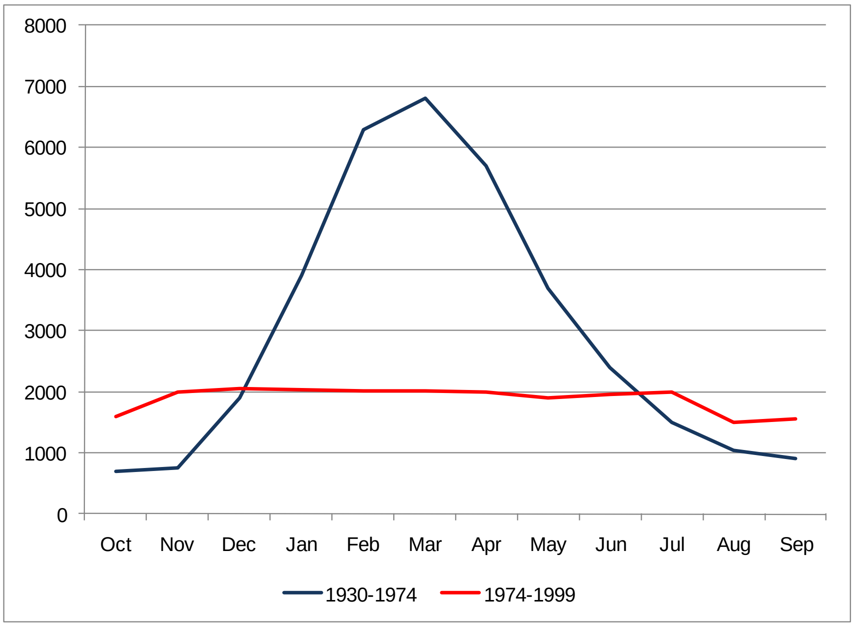


Table 1. Dependence on fisheries and flood-plain recession agriculture for selected rivers.

River basin/Country	People dependent on flood-plain farming and agriculture	People dependent on river and flood-plain fisheries	References
Amazon river basin		780,000	Carolsfeld et al., 2003
Hadejia-Nguru Wetlands, Nigeria	1.5 million farmers, herders and fishermen		Nigerian Conservation Foundation, 2006
Kushiyara and Surma flood-plain, Bangladesh	294,000 dependent on river-flow regime; main sources of income include paddy cultivation (54%), fisheries (4%)		Meijer, 2007
Logone river flood-plain, Cameroon	Waza Logone flood-plain supports 130,000 people		IUCN, 2001
Lower Mekong river, Cambodia, Thailand, Laos and Vietnam		40 million	Sverdrup-Jensen, 2002
Niger river Inner delta, Mali		300,000	Zwarts et al., 2005
Okavango delta, Botswana	33,672 (Ngamiland district)	About 78% of inner and 66% of outer delta households engaged in fishing, and an additional 27% of households in the outer delta were prawn fishers	Kgomotso and Swatuk, 2006; Turpie, 2008
Omo river, Ethiopia	500,000 people live along the lower Omo river valley; nearly 100,000 are heavily reliant on flood-recession farming		EEPCO, 2008a, 2008b
Rufiji river Flood-plain and delta, Tanzania	16,093 households	57% of the households	Turpie, 2000
Sao Francisco river, Brazil		25,000 (early 1980s)	Carolsfeld et al., 2003
Sekong river, Lao PDR		105,000	Lawrence, 2008
Senegal river valley, Mali, Mauritania and Senegal	364,132		Adams, 2000
Sokoto river flood-plain, Nigeria	50,000 (pre- Bakolori dam: 1975)	29,680 (as of 1989)	Hartenbach and Schuol, 2005; Ita, 1993
Sunderban delta (Ganges-Brahmaputra delta), Bangladesh		2 million; 73% of all households are involved in flood-plain fisheries	DOF, 1990 as cited in Craig et al., 2004
Tana river, Kenya	1 million people depend on the river's flooding regime for their livelihoods	54,400 people (out of the 180,000 living adjacent to the Tana river and delta) are dependent on fisheries	Snoussi et al., 2007; Emerton, 1994
Tocantins river, Brazil	At least 100,000 people affected by loss of fisheries, flood-recession agriculture, forage for grazing, and other natural resources		WCD, 2000
Zambezi river, Zimbabwe and Mozambique		54% of households fish 100,000 people employed by prawn fishery	Turpie et al., 1999; Scodanibbio and Mañez, 2005

The indigenous knowledge and institutional structures supporting river-dependent production systems are demonstrated well in the Inland delta of the Niger river. During most years in the past century, 20,000-30,000 km² of the delta's flood-plain were annually inundated. In the mid-1960s over 200,000 farmers, fishers and pastoralists were dependent on the delta (Gallais, 1967). Farmers cultivated a species of floating rice (*O. glaberrima*) during the rising flood and harvested it from local canoes. As the floods receded, they planted a succession of dry-season crops, with those on higher ground benefiting from capillary movement of moisture to their roots. Knowledgeable fishers followed migrating species up and down the Niger as it flowed through and across the delta. Transhumant pastoralists sought inland grazing in the Sahel during the rainy season, but depended during the six-to-nine month dry season on flood-plain grazing.

These time-tested, river-dependent production systems – which are often complemented by migratory and local wage labour, small-scale pump irrigation and business enterprises – continue to be important in the late-industrialising countries in Africa, Asia, the Middle East and Latin America, where the large majority of future dams will be built. What follows is a more detailed look at these production systems.

Fisheries production

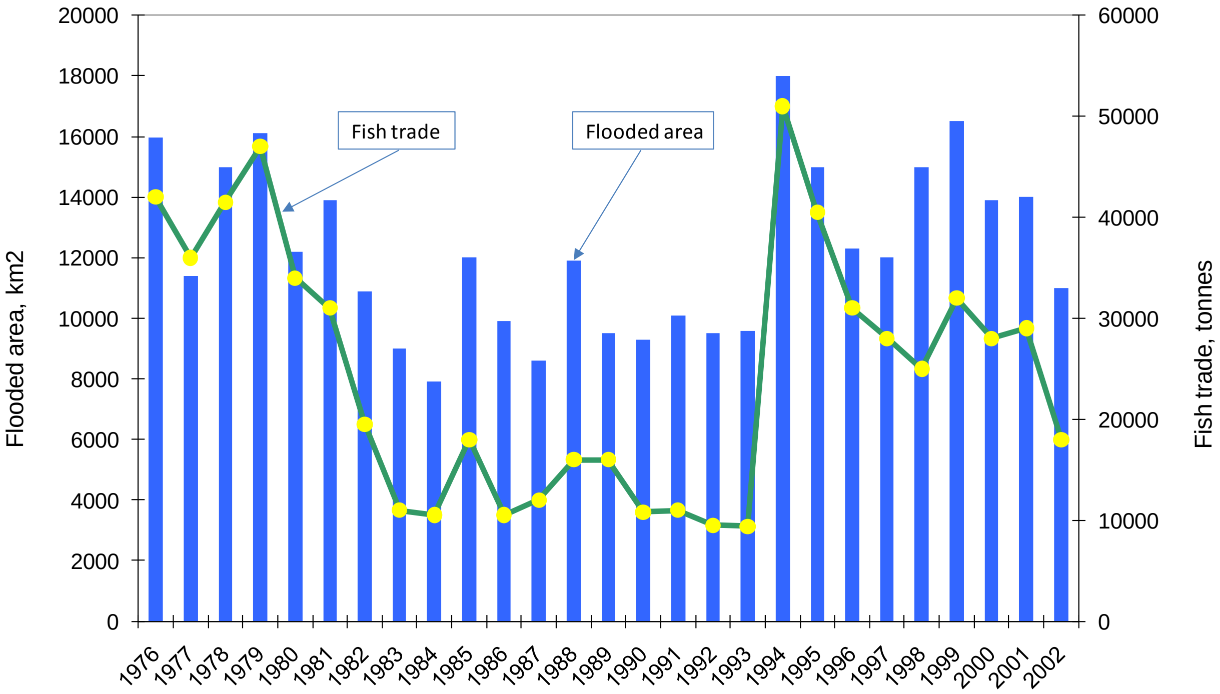
River and flood-plain fisheries are a critical source of food and income for hundreds of millions of people in the developing world, particularly the rural poor. Flood-plains are among the most productive ecosystems on earth (Millennium Ecosystem Assessment, 2005; Opperman et al., 2009). When a fish spawns on a flood-plain, its offspring will have many advantages over other fish born in the river itself. The water spilling into a flood-plain during floods becomes warmer, and is enriched with nutrients, which greatly benefits the growth of young fish. The drowned vegetation of the flood-plain harbours a bounty of insects to feed upon, and provides places where newborn fish can hide from bigger fish and other predators. All of these advantages can play a big role in determining which fish grow fastest, live longest, and reproduce most often. Rivers supporting large numbers of flood-plain-spawning fish species typically produce far more fish tonnage than those without floods and flood-plains (figure 4; Sommer et al., 2001; Koel and Sparks, 2002).

Indeed, comparison studies show that while larger and deeper reservoirs yield fish, on average, at 10-50 kg/ha/y, flood-plains average 200-2000 kg/ha/y (Jackson and Marmulla, 2000). The three key factors supporting this increased productivity in flood-plain rivers are the extent of the flooded area (Halls and Welcomme, 2004; Tockner and Stanford, 2002), flood duration (Koel and Sparks, 2002), and timing of the flood peak (Hoggarth et al., 1999).

When flood-plains are regularly connected to their rivers, they are not only more productive but house the majority of the river's species. In the lower Rhine and Meuse rivers, for example, 70% of the species are found exclusively in the flood-plain lakes (Van Den Brink et al., 1996). Through the survival game of evolution, the advantages of flood-plain habitats have caused many fish species to become so specialised in their genetic make-up that they do not, and cannot, spawn anywhere but in the flood-plain. Ironically, those same genes that enable them to thrive and grow far more quickly by exploiting flood-plain habitats cause their populations to crash when an upstream dam eliminates a river's floods.

For example, the Tocantins river in Brazil once supported a flourishing fishery that provided both cash income and animal protein to riverside communities. When the Tucurui dam was built on the Tocantins in 1984, the fish catch declined by 60% almost immediately, while freshwater shrimp harvests fell by 66% (Fearnside, 1999). Not surprisingly, the number of fishermen declined rapidly as well. In all, at least 100,000 people living downstream of Tucurui were affected by the loss of fisheries, flood-recession agriculture, forage for grazing, and other natural resources (WCD, 2000).

Figure 4. Fish production and trade in the Niger Inner delta is strongly influenced by fish access to the floodplain, represented here by the area of flooding in the previous year (adapted from Zwarts et al., 2005). Bars represent inundated area in km^2; dots represent tonnes of fish trade.



The Tocantins river is not a unique case. Similar losses in fishery resources and livelihoods have been observed following dam construction in many river basins around the world (table 2). A well-documented case is that of Cameroon's Logone river flood-plain known as Waza Logone, which supports more than 130,000 people (IUCN, 2001). In 1979, the Maga dam and a water diversion scheme for rice cultivation diverted 70% of the water supply that once inundated the flood-plain, causing a 30% reduction in the flooded area. As a result, there was a marked drop in flood-recession agriculture and dry-season pastures, as well as a 90% decline in fish yields within the wetlands. The consequent loss of permanent vegetation cover led to a reduction in wildlife that impacted tourism revenues and other economic activities. The monetary losses to the regional economy associated with the reduced flood-plain were estimated at US$2.4 million/y (IUCN, 2001).

While not all the cases are as well documented, a literature review by Jackson and Marmulla (2000) shows that in African rivers, overall fisheries production declined after dam construction. The Senegal river, for example, lost 50% of its riverine fisheries – some 11,250 metric tons/y – after an impoundment blocked the free flow of water from Lake Guiers to the Senegal river (Sagua, 1997). This same FAO review however, shows that while in Southeast Asia declines in wild fisheries yields have been observed and are of deep concern for local food security, they are likely the result of multiple stresses, including dams, overfishing and siltation from deforestation. In Australia, fish catch declines due to dams and water abstraction have affected many species that were once regional favourites, including barramundi, short-finned eel, Murray cod and golden perch (Walker, 1985; Walker and Thomas, 1993).

Table 2. Fisheries status before and after dam construction.

River/Country	Dam(s)	Fish species	Catch or # fish species caught		Reference
			Before dam	After dam	
Kafue river, Zambia	Kafue Gorge dam and Itezhitezhi dam	*Oreochromis andersonii,* a key flood-plain-dependent tilapia species	In 1968, 50% of the catch consisted of the commercially important *O. andersonii*	By 1983, only 3% of catch was made of *O. andersonii*	Acreman, 2000
Kafue river, Zambia	Kafue Gorge dam and Itezhitezhi dam	Increase in predator species: *Clarius gariepinus, Macuseniusmacrolepitus, Labeo maolybdinus, Hepsetus odeo*	Families supported by fishing: 2600 (1977)	Families supported by fishing: 1157 (1985)	Acreman, 2000
Lower Sinu Basin, Colombia	Urra dam		6000 tonnes/y	1700 tonnes/y (early 1990s)	Correa, 1999
Mahanadi river, India	Salandi dam		350 tonnes/y (1960-1965)	25 tonnes/y (1995-2000)	Larinier and Marmulla, 2003
Mun river, Thailand	Pak Mun dam		265 fish species	50 species have disappeared and other species show marked population declines Fish catch decreased by 60-80%	Amornsakchai et al., 2000
Niger river, Nigeria	Kainji dam			30% decrease in catch, and reduction of Mormyridae species from 20% of fish community to 5% (commercially important)	Jackson and Marmulla, 2000
Nile river, Egypt	Aswan High dam		Number of harvested fish species: 47	Number declined to 25 at Assuit and to 14 at Cairo; in Kafr el Zayer reach, number and size increased	White, 1988
Qiantang, China	Xinanjiang dam	*Macrura reevesii*	Freshwater fish: 96 species	85 species	Jackson and Marmulla, 2000
Senegal river, Mali and Senegal	Manantali and Diama dams		23,500 tonnes/y	Reduced by 50% (net loss of 11,250 tonnes/y)	Jackson and Marmulla, 2000
Yangtze river, China	Three Gorges dam	Four species of carp (silver, bighead, grass, black)	Commercial harvest: 3,360,000 tonnes (2002)	1,010,000 (2004), 1,680,000 (2005)	Xie et al., 2007

The benefits from riverine and flood-plain fisheries are rarely taken into account in dam planning and management. Often, the argument made is that newly created fisheries in the reservoir will compensate for the loss of riverine catches. But this argument does not hold true in most of the developing world. First, there is a negative correlation between the size and depth of the reservoir and the productivity of its fisheries; on average, fisheries in large reservoirs are 2-3 times less productive than riverine fisheries (Jackson and Marmulla, 2000). Second, the impacts of fishery losses downstream, in deltas, and in immediate offshore zones can extend to communities hundreds of kilometres away. Third, from a biodiversity conservation perspective, the loss of riverine fish species following damming is a leading cause of imperilment of freshwater fish (Dudgeon, 2010). Finally, in time, reservoirs often suffer from other environmental impacts such as siltation, pollution, eutrophication and algal blooms that cause fish kills and loss of local fishery resources.

The lack of attention to downstream fishery losses is in part due to the paucity of data on the scale, composition, dependence and value of the resource. Riverine fishing communities tend to be dispersed over large landscapes making data collection extremely difficult and often very expensive for government agencies in developing countries. In addition, much of the catch is in the form of small-scale subsistence fisheries, which tend to be consumed locally; therefore, landings are not recorded. This situation is so prevalent in many developing countries that evaluations carried out by the FAO show that actual catches are probably twice or even thrice as large as the reported figures (FAO, 1999). Finally, the species of fish being caught are also largely unknown, with nearly 45% of all inland capture fisheries reported in government statistics simply as 'freshwater fish' (FAO, 1999). In much of Asia, which has the highest inland fisheries production, this proportion can be as high as 80% (FAO, 1995).

These high levels of uncertainty and under-reporting make inland fisheries and the people who depend on them almost invisible to policy makers.

Flood-based agriculture

Fish are not the only species that have learned to take advantage of the environmental benefits provided by floods. Human cultures around the world have developed sophisticated means for exploiting the natural subsidies of water, fresh soil, and nutrients supplied by floods. Some cultures will plant rice just before the flood arrives, and then harvest from canoes or wait until the flood has receded to gather their crops. More common is to plant when the flood peaks in order to take advantage of the increased moisture and nutrients left in the soil as floodwaters recede down the flood-plain slope. Flood-recession farmers have become extremely adept at judging the likely duration of enhanced soil moisture in these areas, and they plant crops that will be most productive under varying circumstances from year to year. Because soil conditions such as the amount of clay in the soil will differ across the flood-plain and change from year to year depending on flooding, these farmers must continually adapt their planting strategies to a shifting mosaic of flood-plain conditions.

Flood-recession agriculture is an age-old practice in Africa, extending back at least to 5000 years in the case of Egypt’s Nile valley. The presence of early-maturing and drought-resistant varieties of millet and sorghum suggests that flood-recession cultivation was historically widespread on the continent (Scudder, 1991). The eleventh-century historian al-Bakri described the practice in the Senegal river valley: "The inhabitants sow their crops yearly, the first time in the moist earth during the season of the… flood" (Horowitz and Salem-Murdock, 1993). In good years, between 300,000 and 500,000 ha were used for flood-recession cultivation in the Senegal, Niger, and Lake Chad basins (Scudder, 1991; Postel, 1999).

When the Bakolori dam was built on the Sokoto river in Nigeria in the late 1970s, it sent the flood-recession farming culture of the valley’s 50,000 inhabitants into disarray (Adams, 1985, 2000). The dam affected the timing of the flooding downstream, and reduced both its extent and depth on the flood-plain. This meant that farmers no longer knew what to expect from the floods, and their ability to match expected flooding and soil conditions with appropriate crop types broke down. Rice and sorghum cultivation during the flooding season became riskier and unpredictable. Other areas became too dry for rice yet too easily waterlogged by rainstorms to support dryland crops such as millet. Before the dam was built, more than 90% of the flood-plain was cultivated for crops. In some villages, that proportion dropped to 3% after damming (Adams, 1985). Crop yields declined precipitously, resulting in losses of more than US$400,000/y. Ironically, the Bakolori dam was built on the premise of increasing revenues from irrigated agriculture. According to Adams (1985), had the cost of lost flood-recession agriculture been accounted for in the dam's plans, it is quite likely that Bakolori would never have been built.

Because dams can provide a more regular and dependable supply of irrigation water to downstream areas, there is considerable potential to improve agricultural productivity. However, the beneficiaries of these new agricultural opportunities do not always include the original inhabitants of the downstream flood-plains. In some instances, politically favoured immigrant farmers have evicted long-term flood-plain residents, as in Mauritania following construction of the Manantali dam (Horowitz, 1991) and in Somalia after the decision was made to build the Baardheere dam on the Juba river (Besteman and Cassanelli, 1998).

Livestock management and other livelihood and cultural dependencies

The availability of flood-plain grazing is critical for the survival of livestock managed by both riverside communities and transhumant pastoralists, especially those in arid and semiarid regions, and especially toward the end of the dry season when water levels usually reach their lowest point. During the rainy season, inland grazing is temporarily available, but as the quality and quantity of these inland pastures deteriorate, the importance of flood-plain grazing increases.

Though flood-plains are restricted in size in comparison to inland areas, livestock graze a variety of highly nutritional grasses that have varying tolerances for flooding. In wetlands in Central Africa, for example, cattle and wildlife graze on extensive 'carpets' of *Panicum repens* after flood waters recede. At the water's edge they graze on *Echinocloa* and, wading out into the water, they feed upon floating mats of *Vossia*. Dam-regularisation of river flows for energy production, irrigation, and flood control has caused widespread loss of these vital flood-plain resources. In the absence of flooding along the dammed Kafue river in Zambia, *Vossia* is being replaced by *Typha* species that are far less desirable for grazing.

Naturally flowing rivers also provide river-dependent communities with timber, fuel, and a wide variety of edible, medicinal and other useful plants and wildlife. The availability of these resources typically decreases when river flows are altered by dams. Aquifer recharge also diminishes, so that groundwater wells are more apt to dry up. The structure, aridity and fertility of arable land on higher, less-frequently flooded areas are also adversely affected – for example, through reduced capillary movement of moisture and increased grazing pressure when flood-plains become less suitable for grazing. Finally, the loss of less tangible but important cultural and spiritual values stemming from naturally flowing rivers is a frequent complaint of those who are involuntarily resettled in inland areas from riverside communities after dams are built (Downing, 1996).

Economic valuation of riverine production systems

Unfortunately, very few economic studies have been conducted to assess the monetary value of river-based production systems such as fisheries and flood-plain farming and grazing. However, the few studies that have been conducted suggest that their economic value can be substantial and that their omission from project assessments can skew not only the distribution of project benefits but the project's overall net value (Adams, 2000; Schuyt, 2005; Zwarts et al., 2005). For example, hydropower benefits from the Sélingué dam on the Niger river in Mali are estimated to total some €10.7 million/y, but the dam has reduced the value of fishery benefits by an estimated €4.2 million/y, with the benefits largely flowing to urban populations and the costs borne by rural inhabitants along the river (Zwarts et al., 2005). Likewise, the proposed Fomi dam on a tributary of the Niger river has been projected not only to produce €18 million/y in electricity benefits, but to generate losses in fisheries and biodiversity benefits valued at €14 million/y. Excluding the lost value of these riverine production systems both prevents adequate compensation to the rural populations who incur the losses and produces a misleading estimate of the project's overall net value.

Research in north-eastern Nigeria has documented returns from flood-dependent production systems that are actually higher than for dam-supplied irrigation schemes that would disrupt those riverine production systems. A vast flood-plain wetland area below the junction of the Hadejia and Jama'are rivers provides food and income sources for many rural Nigerians who use it to graze animals, grow crops, collect fuel-wood, and to fish. The flood-plain also recharges regional aquifers, which are vital water supplies in times of drought. The Hadejia-Jama'are wetlands also provide dry-season grazing for semi-nomadic pastoralists and critical habitat for migratory waterfowl. With the flood-plain increasingly threatened by dams and irrigation schemes, Barbier and Thompson (1998) evaluated the economic benefits of direct uses of the flood-plain – especially for agriculture, fuel-wood, and fishing – and compared these with the economic benefits of the irrigation projects.

They found that the present value of net economic benefits provided by the use of the natural flood-plain exceeded those of the irrigation project by more than 60-fold (analysed over time periods of both 30 and 50 years). Since water is a limiting factor in the region, Barbier and Thompson (1998) also compared the options on a per-unit-water basis and found the benefits of the flood-plain to range from approximately US$9,600 to US$14,500/m^3 compared with US$26 to US$40/m^3 for the irrigation project. Had Barbier and Thompson been able to estimate habitat availability, groundwater recharge, and other critical ecosystem benefits provided by the intact flood-plain, the disparity in values would have been even greater.

THREE CASE STUDIES

The nature of human dependence on rivers and the potential impact of dams on river-based production systems and local communities can perhaps best be understood through illustrative case studies. Below we describe the cultural practices, ecological conditions, and dam-related threats to human well-being on three rivers as a means for giving the reader deeper insight into the ways in which downstream human livelihoods and well-being can be disrupted by dam-building. Only one of these rivers (Kafue) has already been dammed; the other two (Xe Bang Fai and Omo) are threatened by dams now under construction. Our decision to portray two rivers that are only now being dammed was made on the basis of information availability: it is only recently that detailed socio-economic information on downstream communities has begun to be reported in environmental assessments and other project-related documentation.

For the vast majority of the more than 50,000 large dams built to date, very little documentation exists of pre-dam social conditions. Consequently, it is difficult to assess impacts beyond a qualitative description of likely disruptions to flow-dependent ecosystems and communities.

Kafue river, Zambia

The Kafue Flats is a seasonally flooded landscape of oxbow lakes, verdant grasslands and wooded islands providing habitat for an endemic antelope, 67 species of fish, and over 450 bird species (Ramsar Designation for Kafue Flats, 2007). The Flats also support a rich small-scale economy of cattle-grazing, fisheries and agriculture, as well as large sugarcane farms.

Historically, the Flats flooded seasonally during a distinct rainy season. Since completion of the Itezhitezhi dam and its 400 km^2 reservoir in 1978, however, the flow regime of the Kafue river has been altered substantially. The primary purpose of the Itezhitezhi dam is to control flows for the downstream Kafue Gorge dam, which generates power for Zambia's capital city and the Copperbelt mines. The alteration of the natural seasonal flood has negatively impacted both the flood-plain ecosystem and the downstream communities who rely on it for economic and food security.

Itezhitezhi was one of the first dams to include operating rules for managed flood releases to benefit the downstream ecosystem. The dam management agency has been reluctant to release these environmental flows, however, due to an inability to accurately predict how much water is likely to be available for power generation; if too much water is released for environmental flow purposes, the dam managers may be at risk of running short of the water needed to generate electricity in later dry months. Considerable effort is now being given to developing more accurate forecasting models, with the hope that these tools will give the dam managers greater confidence to release environmental flows.

Since 1978, in the absence of proper environmental flow releases, the operation of the dam has severely impacted flood-plain vegetation, fisheries, waterbirds, and food production systems. With changes in habitat and food sources on the flood-plain, combined with poaching, the population of the Kafue lechwe (*Kobus leche kafuensis*), an endemic semi-aquatic antelope, has declined from 68,000 in 1995 to 38,000 in 2006 (Ramsar Designation for Kafue Flats, 2007).

Cattle, a cultural touchstone for the Ila ethnic group and a traditional source of much of their wealth, have been affected as well. Cattle graze in upland areas during the rainy season and are driven to the Flats at the onset of the dry season to graze on the nutritious grasses. The unpredictable water conditions induced by Itezhitezhi have caused herders to stay in the uplands for longer periods, leading to damage to neighbours' crops, increased exposure to ticks, and reliance on inferior forage and limited water supplies. During the mid-1980s and 1990s, cattle populations were decimated due to the tick-borne corridor disease. With insufficient flooding to flush ticks out of the area, cattle faced higher exposure to the disease.

As in many rivers, fish breeding in the Kafue is highly dependent on natural flooding patterns. The flooded grasslands are the spawning ground of breams and several other fish species. The elimination of flooding in the main river due to the Itezhitezhi dam has disrupted the timing and extent of access to the flooded grasslands, with consequences for the diversity and abundance of fish.

A complex network of fishers and traders supplies local families, upland towns and the capital of Lusaka with large supplies of dried and fresh fish. Traders travel from several hours away and stay days at a time, often trading inland crops such as sweet potatoes and maize for the fish. Thus changes in the productivity of the Kafue Flats can have a large impact on populations that seem removed from it, but in fact are deeply connected. These longer-distance impacts on social systems are not accounted for in conventional methods for estimating 'potentially affected' people, as described later in this paper.

Xe Bang Fai river, Lao PDR

The Xe Bang Fai river flows from the mountainous border between Lao PDR and Vietnam to its confluence with the Mekong river. In the near future, 150 km of the river's middle and lower reaches will be substantially altered by increased flows from the Nam Theun 2 (NT2) Project. Unlike most dam projects, NT2 affects two rivers. The dam has been built on the Nam Theun, on the edge of a high plateau. Water is then diverted from the dam's 450 km^2 reservoir down a steep escarpment to a power station, and then into the Xe Bang Fai through a 27-km channel, doubling the annual average flows in the Xe Bang Fai. Over 75,000 Xe Bang Fai basin people living in 82 riverside villages and 101 hinterland communities will likely be directly affected by expected changes to the river ecosystem (International Environmental and Social Panel of Experts, 2007; Nam Theun 2 Hydroelectric Project, 2008).

Seasonal fish migrations in the Xe Bang Fai are essential to fisheries supporting riverside communities as well as seasonal fishers from nearby villages (Shoemaker et al., 2001). Lao PDR villagers use a variety of traditional practices for catching fish, which depend on the seasonal flood cycle of the river. The *pa doke keo* fishery takes place at the beginning of the rainy season, when this fish is migrating up the Xe Bang Fai from the Mekong. Following this fish migration there is considerable fishing activity in flooded wetlands throughout the rainy season. In October, as the rainy season ends, lift nets are used to catch small cyprinid fish species and gill nets are set for larger species. At the same time, other fish are moving out of rice fields, streams, oxbow lakes and inundated natural depressions to return to the main rivers. Barrier traps are used at the edges of rice fields and on streams to catch large quantities of these fish.

Besides fish, women and children collect other aquatic foods from the river and its tributaries and wetlands (Shoemaker et al., 2001). These aquatic resources include shrimp, snails, earthworms (used for fish bait), frogs, crabs and aquatic insects. While much of this harvesting is for subsistence purposes, some people realise substantial income from the sale of these products.

In most households, livestock is a major source of income, particularly in the lower Xe Bang Fai basin. Water buffaloes, cows and pigs act as *de facto* 'banks' for many families. Animals can be sold for cash during times of particular need, such as during rice shortages or illness of a family member, or to pay the costs of wedding and funeral ceremonies. Along the Xe Bang Fai, pigs forage for worms along the river banks, water buffaloes wallow in the river and eat large amounts of algae and other water plants, ducks swim and feed in the river, and chicken, goats and cows drink from the river and forage vegetation along its banks. These 'free' services provided by the Xe Bang Fai reduce the amount of resources that the owners of livestock would otherwise need to provide to these animals, reducing people’s workloads and making the raising of livestock an efficient economic activity.

Many of the villages and rice fields in the Xe Bang Fai basin are surrounded by seasonally flooded forests dependent on the natural flooding cycle. These forests include many edible perennial and annual plants as well as edible insects and aquatic animals that rely on these flooded forests. Many species are adapted to the seasonal rise and fall of the rivers’ water levels. Villagers also harvest bamboo, rattan, mushrooms, honey, resin, and many other products.

Beginning in 2010, the NT2 project will not only double Xe Bang Fai annual flows but will also regularise them to a considerable extent. This means that dry-season rapids, important for breeding for some fish species, will no longer exist. Changes in monthly flows are expected to affect migratory fish coming from and returning to the Mekong. Fishers will also have to learn new techniques if they are to cope with new conditions, although the exact nature of these, and other impacts, will only be known once the project is completed.

Omo river, Ethiopia

The Omo river has a long and storied history. The family tree we all share – that of Homo sapiens – has roots in the Omo river valley. In 1967, Richard Leakey unearthed human skulls from the valley that are nearly 200,000 years old. Stone tools found in the area suggest that hominids have been living in the Omo for four million years. More than 500,000 people comprising 16 distinct ethnic groups currently live along the 500 km of the lower Omo river valley (EEPCO, 2008a, 2008b).

What the future holds for these half-million people in the Omo river valley is highly uncertain. Gilgel Gibe III – which will become one of the world’s largest dams – is scheduled for completion in 2013. For residents of Addis Ababa, the capital of Ethiopia, the new dam’s electricity supplies will be a welcome development: as recently as June 2009, many city residents were experiencing blackouts at least three days a week (Fente, 2009).

The reservoir behind the 240-metre Gibe III dam will submerge more than 150 km of the Omo river gorge (EEPCO, 2008a, 2008b). The dam’s influence will extend far beyond the 29 houses lost at the site of the new reservoir, however. As noted in environmental impact statements for the project (EEPCO, 2008a), the lifestyles and well-being of the half-million villagers living downstream of the dam are vulnerable to expected changes in the river’s flow.

Nearly 100,000 members of the Dasenech, Mursi, Mugugi, and six other ethnic groups are heavily reliant on flood-recession farming. The villagers plant a wide variety of crops including staples such as sorghum, maize and beans. Their choice of which crop to plant at different levels of the flood-plain draws from an inter-generational legacy of knowledge, accumulated from thousands of years of experience with the vagaries of climate and flooding.

Other ethnic groups such as the Bacha and Karo depend almost entirely on fish. Of the 70 fish species known from the Omo and Lake Turkana, at least nine are found nowhere else on earth. The life cycles of these fish are tightly synchronised with the fluctuations of the river. The rising of the river in June triggers their spawning migrations. The floods of August and September enable them to give birth in warm, nutrient-rich water on the flood-plain. Then the slowly receding water levels in October and November pull the newborn fish out of flood-plain lakes and back into the main channel of the river.

No one knows how these fish and flood-plain crops will fare under the discordant rhythm set by Gibe III. But it is fairly certain that the long-running human-crop-fish choreography of the valley will be substantially disrupted by the dam's rescheduling of water flows. The dam's designers have proposed to replace the natural five-month flood cycle of the Omo with a 10-day long 'controlled flood' to be released from the dam each year. This proposed flood will be quite small compared to natural floods, and would inundate and nourish only a fraction of the 100 km^2 of flood-plain and marshlands in the valley (EEPCO, 2008a, 2008b). On the other hand, highly unnatural floods nearly as large as the annual controlled floods will result from electricity generation on a daily basis.

Critics of Gibe III have challenged claims by the dam's architects that the controlled flood will sustain the river's fishery and flood-recession agriculture (Business Daily, 2010). These critics suggest that the proposed artificial flood's scale and duration differ so much from the natural flood that many critical ecological links are bound to be broken, with potentially disastrous social and ecological consequences for the half million people whose livelihoods depend upon the river's natural flow pattern.

METHOD FOR ESTIMATING DOWNSTREAM POPULATIONS POTENTIALLY AFFECTED BY LARGE DAMS

We began this study by building a global database of case studies in which researchers had documented the impacts of dams on downstream, river-dependent communities. That database, which now includes more than 120 rivers in at least 70 different countries (available upon request from the lead author), provided us with initial insights into the number of people who have been affected downstream of large dams. They also provided reference benchmarks from which we subsequently developed a global estimate of downstream dam-affected people.

To our knowledge, there is currently no global estimate of the number of downstream people that may have been impacted by dam-induced alteration of river flows and other ecosystem conditions. We offer here a globally consistent approach, supported by a Geographic Information System (GIS) analysis, to estimating a 'potentially affected' population downstream of large dams. By using the term 'potentially affected' we are attempting to account for people who are either exposed to reduced food security and availability of ecosystem goods and services, or have to make adjustments in their livelihoods in response to dam-induced changes in the river environment. The degree to which they are actually impacted may then depend on many more variables, including both the extent to which they were dependent upon the river ecosystem originally and the availability of other livelihood options and economic opportunities.

A well-documented case study of the 400 km^2 flood-plain area bounded by the Surma and Kushiyara rivers in Bangladesh illustrates the complex nature of human livelihood options available in many river basins, and the difficulty of assessing which people have been 'potentially affected'. Of the estimated 294,000 occupants of this flood-plain area in 2000, 54% of households depended upon flood-supported agriculture (paddy cultivation) as their main source of income, compared with 4% on fishing and 41% on 'other' activities that are not associated with river flows. This latter category included non-agricultural labour, handloom, various businesses, construction trades, and transportation (Meijer, 2007). While 58% of these households are largely dependent on the river's historic patterns of river flow for these economic activities, there is considerable variance in the degree to which any family will be affected by damming. Many household residents pursue more than one form of economic activity, particularly in different seasons, and most households have more than one wage earner. It is difficult to predict how the balance of livelihood options will shift as river flows become substantially altered by a planned upstream dam (Tipaimukh dam in India). Fishers and paddy farmers will certainly be affected adversely, while boat transport, laundry, or stone mining may become more dependable if river flows are stabilised.

In estimating the number of potentially affected people in the Surma-Kushiyara flood-plain following damming, virtually all of the flood-plain residents could be included by reason of the fact that the entire flood-plain is presently inundated each year. While each of these flood-plain dwellers might be expected to benefit from dam control of flooding, it is important to note that very few dams are able to completely control the most extreme floods. Quite commonly, the false security of an upstream dam has enticed further encroachment into flood-plains and loss of traditional patterns of seasonal migration between river and upland camps, often to disastrous consequences when extreme floods escape the control capacity of the dam.

In developing our global estimate of the number of people potentially affected by dams, we have made a number of conservative assumptions to accommodate data uncertainties and the lack of detailed information for the vast majority of dammed rivers (figure 5). First, we examined only those rivers impacted by the ~7000 largest dams worldwide. These dam locations have been geo-referenced in a new global reservoir and dam database (GRanD) developed by the Global Water System Project (Lehner et al., *in prep*.), and linked through GIS with the global river network HydroSHEDS (Lehner et al., 2008). Collectively, these reservoirs account for more than three-quarters of the estimated total global reservoir storage capacity.

Second, we defined 'impacted rivers' as those in which total upstream reservoir storage capacity exceeds 10% of the long-term annual river discharge. Reservoirs with a degree-of-regulation (d-o-r) ratio of more than 10% are typically capable of significantly altering daily and monthly flow regimes as well as reducing peak and elevating base flows. The Three Gorges dam, for instance, can store only 4.5% of the total annual average flow of the Yangtze river, but its design purpose is to eliminate smaller floods and reduce larger floods, and it has altered the downstream sediment transport significantly (Xu and Milliman, 2009). Reservoirs able to store more than 100% of a river's annual flow typically cause the greatest alterations in downstream flow patterns, because water releases from the dam can almost entirely be timed to meet human demands for water, electricity, and/or flood control; thus, little of the natural flow regime is maintained. In their global assessment of dam impacts on rivers, Dynesius and Nilsson (1994) identified a large number of rivers as being 'moderately' or 'strongly' affected by dam regulation, many of which have a degree of regulation less than 10%. However, for our global analysis we conservatively set a minimum threshold for 'impacted' rivers at 10%. For our region-specific analyses, we categorise river reaches into increasingly higher levels of impact severity according to d-o-r ratios of 10-25%, 25-50%, 50-100%, and >100%.

Third, we assume that people living within 10 km of an 'impacted' river are most at risk, and located these populations using the database of the Global Rural-Urban Mapping Project (GRUMP) at 1 km resolution (CIESIN et al., 2005). We believe this to be a conservative zone of influence based on our review of the 120 rivers in our literature database. For instance, even on medium-sized rivers such as the Kafue in Zambia and the Xe Bang Fai in Lao PDR as described earlier in our case studies section, people living within 10 km of these rivers participate considerably in fisheries and other river-dependent activities; and, in fact, trade networks extend to a considerable distance beyond the zone where harvesters of river goods reside.

Fourth, we assume that people living in flood-plains are more directly affected than those in upland or steep parts of a river valley. We thus excluded people living in areas where land surface slopes exceed 1 degree.[2] This criterion also tends to reduce the 10-km zone of influence around smaller rivers which are often located in steeper headwater regions. Fifth, we assume that rural dwellers will be more

[2] We used the digital elevation model of the HydroSHEDS database at 500 m pixel resolution for this calculation.

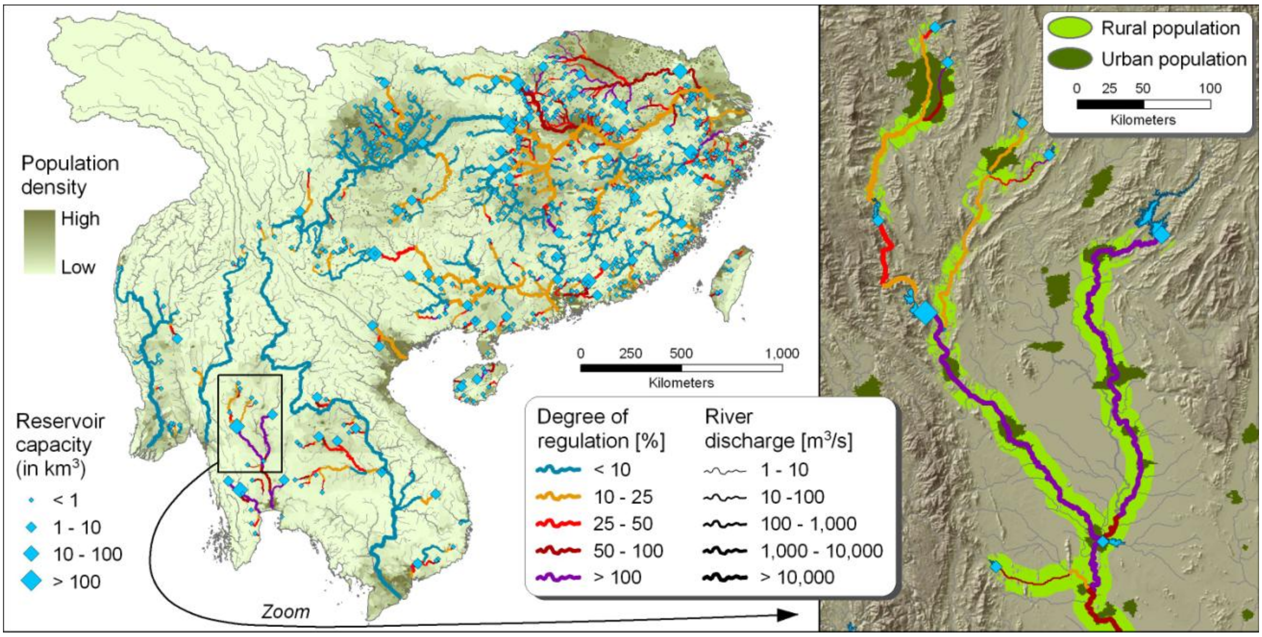
directly dependent on historic patterns of river flow and associated resources than urban dwellers, and again used the GRUMP database to make this distinction (figure 5, right panel).

Last, we have explicitly included 30 of the largest delta areas globally and assigned to each of them the degree of regulation of their associated main-stem river. We used the delta outlines derived by Syvitski et al. (2009) and added, as we did for rivers, a 10-km zone of influence (excluding slopes of more than 1 degree) to calculate the potentially affected rural delta population. The inability to account for all deltas worldwide, due to lack of information, continues to render our results conservative.

Zeroing in on one important region, figure 5 (left panel) illustrates the spatial distribution of impacted rivers downstream of dams in Southeast Asia. This area represents a region of high population density (total population is 1.8 billion) and strong traditional ties between people's livelihoods and rivers, including, for example, the basins of the Mekong and Yangtze rivers.

As a test of our approach, we compared our GIS-generated estimates with some of the case studies summarised in table 1. The results of this comparison (table 4) suggest that our approach generally underestimates the number of affected individuals in most cases. However, our estimates are sufficiently comparable to those documented in published studies to give us confidence that we have generated reasonable, but conservative, estimates for the number of potentially affected people.

Figure 5. Illustration of the method used to estimate the size of downstream populations.



Left panel: Large reservoirs of Southeast Asia and their downstream impacted rivers; only those river reaches coloured orange, red, and purple are included in the assessment, blue ones (degree of regulation < 10%) are excluded; grey rivers have no large dams upstream. Right panel: Zoom showing the 10-km zones of influence around the affected rivers; areas steeper than 1 degree are excluded; only rural populations in these buffer zones are counted in the assessment (light green); urban populations (dark green) are excluded.

Table 4. Comparison of GIS-generated estimates from the study with numbers of affected people documented in the literature.

River name	GIS-generated estimate of number of potentially affected people	Number of affected people documented in published studies	Reference
Niger river inner delta, Mali	367,000	300,000 fishers	Zwarts et al., 2005
Senegal river valley, Mali, Mauritania and Senegal	231,000	364,132 farmers	Adams, 2000
Sokoto river flood-plain, Nigeria	174,000	50,000 farmers; 29,680 fishers	Hartenbach and Schuol, 2005
Hadejia-Nguru wetlands, Nigeria	670,000	1.5 million farmers, herders and fishers	Nigerian Conservation Foundation, 2006
Tana river, Kenya	319,000	1 million farmers; 54,400 dependent on fisheries	Snoussi et al., 2007; Emerton, 1994
Rufiji river flood-plain and delta, Tanzania	56,000	16,093 farming households	Turpie, 2000
Sekong river, Lao PDR	26,000	105,000 fishers	Lawrence, 2008

Table 5 provides our estimated numbers of potentially affected people, classified by severity of river impact. Globally, altogether 472 million people live in rural areas downstream of the ~7000 largest dams, at a distance of less than 10 km from the nearest 'impacted' river. Of these, 91 million live near the most severely impacted rivers (with d-o-r ratios exceeding 100%). Two river basins – the Ganges-Brahmaputra and the Yangtze – stand out with dense concentrations of rural populations (144 million and 82 million, respectively). The Ganges-Brahmaputra estimate is particularly high due to the affected delta population reaching 105 million alone. Globally, more than one-third of the potentially affected populations live in river deltas; among the most populous are those of the Ganges-Brahmaputra, Yangtze, Niger and Nile rivers, while the Mekong and Irrawaddy deltas are below the 10% d-o-r threshold.

As the global layer of impacted rivers (Lehner et al., in prep) also includes an attribute of river size, we further distinguished our results for small (< 10 m^3/s), medium (10-100 m^3/s), large (100-1000 m^3/s), and very large (> 1000 m^3/s) rivers (table 5). We found that globally 232 million people live in rural areas downstream of large dams close to (< 10 km) very large impacted rivers (discharge > 1000 m^3/s) for which the total upstream storage capacity exceeds 10% of the annual flow. As illustrated by table 5 and figure 6, the potentially affected populations are heavily concentrated in Southeast Asia and India, where together more than half of all large dams have been built in the world's most populous region.

A NEW WAY FORWARD WITH DAMS

In this paper we have described the nature of human dependence on river ecosystems, focusing on rural riparian populations whose livelihoods and well-being are strongly connected to river health. The natural productivity of healthy river ecosystems provides vital food security for a sizeable proportion of the global population. Unfortunately, dams have disrupted the natural ecological processes that sustain river productivity, with great consequence for river-dependent people.

Table 5. Number of 'potentially affected' rural people (in millions) living downstream of large reservoirs close to (< 10 km) rivers, tabulated by degree of regulation and by river size.

Region	Total	By degree of regulation (cumulative upstream storage capacity in % of average annual flow)				By average river discharge (in m^3/s)			
		10-25	25-50	50-100	> 100	1-10	10-100	100-1000	> 1000
Africa	40.5	3.9	17.9	4.8	13.9	4.6	6.6	5.5	24.0
Asia	399.6	217.4	57.5	58.7	65.9	38.8	84.5	74.4	201.9
Australia	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Europe	17.0	5.1	2.7	2.5	6.8	2.4	5.2	5.4	3.9
North America[a]	8.7	2.3	2.0	1.9	2.5	2.1	3.1	2.4	1.0
South America[b]	5.7	1.0	0.9	2.0	1.7	1.0	2.0	1.8	0.8
Global total	472.3[c]	230.0	81.2	70.2	91.1	49.2	101.7	89.8	231.7
Deltas alone	188.9	148.9	14.6	3.2	22.2	0.0	0.0	4.8	184.1
South-East Asia[d]	112.9	58.2	15.4	22.8	16.6	13.9	30.3	23.8	45.0
China	143.1	55.0	15.9	30.2	42.0	26.7	44.2	22.0	50.1
India	122.6	63.4	26.2	17.6	15.3	9.5	31.3	29.3	52.5
Bangladesh	89.7	87.4	2.3	0.0	0.0	0.0	0.0	2.3	87.4
Nigeria	21.7	1.5	15.7	1.9	2.6	2.0	3.0	1.5	15.2
Pakistan	15.3	1.4	8.0	5.9	0.0	0.1	0.5	7.9	6.9
Thailand	8.4	1.3	1.8	1.3	4.0	0.4	2.1	5.8	0.1
USA	8.2	2.1	1.8	1.8	2.5	2.1	3.1	2.2	0.8

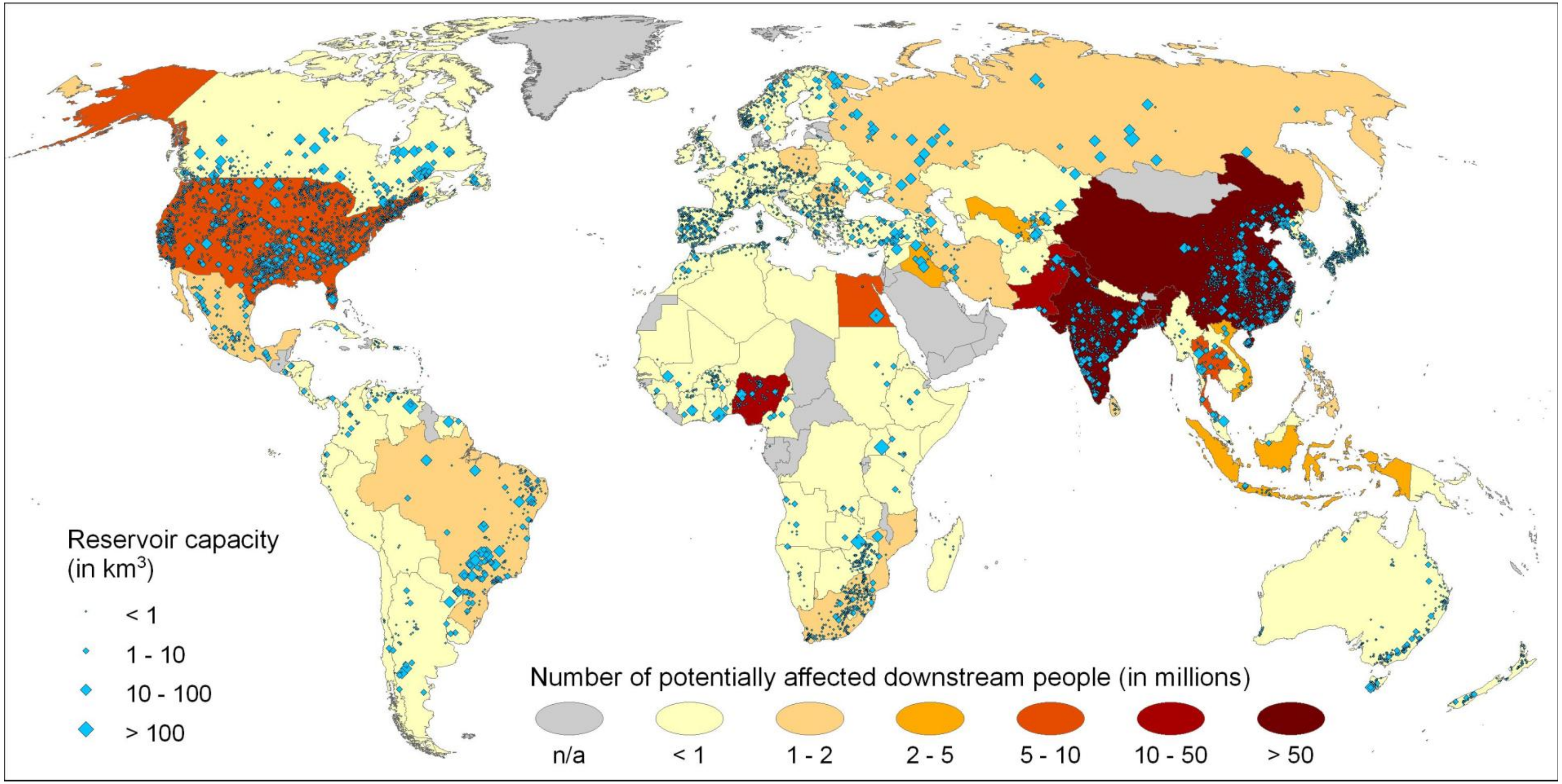
[a] Including western Russia and Middle East. [b] Including Central America and the Caribbean. [c] If urban areas are included, this number becomes 1101.4 million. [d] As defined in figure 6.

We readily acknowledge that dam development projects have played a very important role in advancing local and national economies, and have in many instances provided new livelihood opportunities, improved access to water and electricity, enhanced crop production through irrigation systems, and contributed to poverty alleviation. Many dam development projects have also provided ancillary benefits to local communities, such as health and educational programmes and occupational training. The fact that dam development projects can provide important local to national benefits, including benefits that flow to downstream communities is not at issue here.

What is at issue is the degree to which dam projects degrade the natural food productivity of river ecosystems and disrupt livelihoods and cultures dependent on these ecosystems without an accurate accounting of these costs. Moreover, as described below, many of these negative consequences can be avoided by applying pragmatic 'best practice' approaches.

The WCD Report and this paper call for a new way forward in dam development. Below we summarise three key steps on the pathway toward a more sustainable approach to dam development. The practices described here are not new or untested; on the contrary, they have been advocated by many within the dam industry itself, and the ecological and social benefits of these approaches have been well demonstrated (Postel and Richter, 2003; Opperman and Harrison, 2008; Richter and Thomas, 2007; Krchnak et al., 2009). The World Commission on Dams report included a large library of supporting documents that describe many relevant case studies documenting pragmatic means for avoiding or mitigating the impacts of dams (WCD, 2000).

Figure 6. Distribution of 'potentially affected' rural people living downstream of large dams close to impacted rivers (numbers are totals per country).



The three steps highlighted below can be applied both to new dam projects and existing projects. Some authors of this paper have been directly involved in a number of dam 're-operation' and development projects which suggest that substantial ecological and social benefits can be regained through cost-effective 're-operation' of existing dams (Postel and Richter, 2003; Richter and Thomas, 2007), or by fully integrating social and environmental considerations into new dam projects.

For example, as part of the Sustainable Rivers Project, a partnership between the US Army Corps of Engineers and The Nature Conservancy, the operations of large dams in four river basins have been modified to accommodate environmental flow releases designed to restore downstream river ecosystems (The Nature Conservancy, 2010). In all four basins, beneficial adjustments in dam operating rules have been accommodated with minimal or no consequences for hydropower, water supply, or any other operating purpose. For instance, ecologically beneficial high-flow releases from dams in the Savannah (Georgia and South Carolina), Bill Williams (Arizona), and Green river (Kentucky) basins have been achieved simply by changing the timing and volume of flood-water releases from the dams (Postel and Richter, 2003). In fact, on the Green river, operational changes resulted in substantially improved flood risk management and extension of the recreational season on the reservoir, providing an economic boost in a poor rural area.

In another evaluation of re-operation potential to restore modest but essential levels of flooding in the Zambezi delta, Beilfuss and Brown (in press) concluded that managed floods could be reinstated with very little impact (1.4-2.3%) on hydropower production at Cahora Bassa dam in Mozambique. Similarly, substantial *increases* in hydropower production and associated revenues are being projected under an ongoing redesign of the operational plans for four new dams being built on the Yangtze river upstream of Three Gorges dam in China (Harrison et al., 2007). This redesign involves restoring the flood-plain's lake and wetland ecosystems, and their associated fish and other food resources, such that the Yangtze flood-plain can once again safely accommodate flood inundation. This strategy could substantially alleviate the flood storage requirements of the four new upstream dams, enabling much greater production of hydropower while preserving important ecosystem functions.

In some cases, it can be expensive to modify the operations of existing dams, however, particularly when they are centrepieces of regional electricity grids or integral components of large-scale irrigation projects. Modifying the operations of Glen Canyon dam on the Colorado river in the western United States has resulted in losing about one-third of the dam's electricity generation potential (GCDAMP, 2010). The US government has justified this lost hydropower on the basis that it is necessary to protect the ecological integrity of one of the country's iconic ecosystems, the Grand Canyon, along with federally listed endangered species.

A key lesson learned from efforts to integrate environmental and social considerations into dam projects is that it is far-less expensive and more socially and politically acceptable to include such accommodations early in the design of new projects (Krchnak et al., 2009). Such early consideration results in dam development projects that maximise dam benefits while minimising undesirable ecological and social impacts. Here we describe three essential steps for achieving optimal results. It is important to note that the first step must be included as part of national, multinational or river-basin planning; national governmental leadership is essential for success in this step. This sets the context for the second and third steps, which are focused on specific dams or cascades of dams.

Step 1: Integrated river basin planning – Stakeholder surveys, options assessment, and dam siting

By far, the single most effective dam development strategy for protecting ecological and social values associated with river ecosystems is to avoid constructing dams in the wrong locations (Ledec and Quintero, 2003; Harrison et al., 2007; Opperman and Harrison, 2008; Krchnak et al., 2009). Successful water resource development requires planning at the scale of entire river basins or even larger geographical scales, from which the interactions between ecological processes, human dependencies on river and estuary ecosystems, and options for infrastructure and other forms of economic development can be viewed optimally.

Sufficient investment of time and money in conducting stakeholder surveys is essential to understanding human connections to rivers, options for the future, and avoiding or minimising social impacts of dams. Stakeholder appraisal and surveys of river-dependent people should assess the demographic, socio-economic and health status of river basin inhabitants. This includes assessment of local farm and non-farm employment and production, fishing and other forms of resource harvesting, and of trading and processing at the household, village and township levels. Also required is evaluation of the development potential of the river basin, including not just the potential benefits to be derived from dam projects but also other forms of economic development, based on active stakeholder involvement and their preferences.

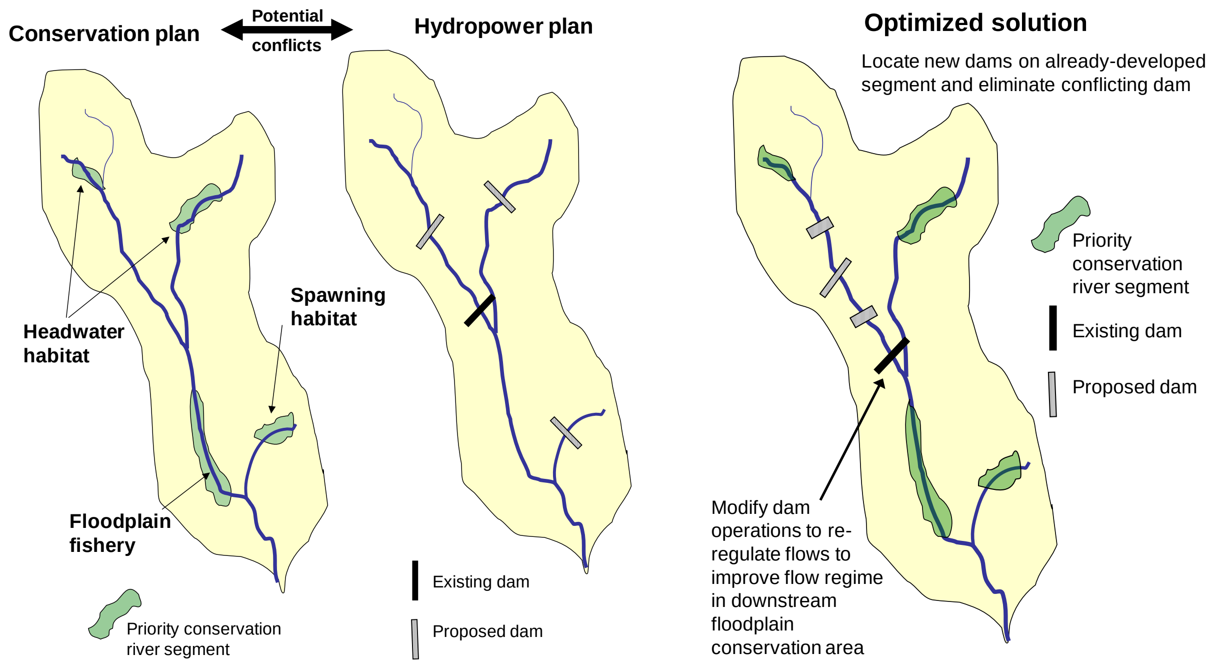
The goal of stakeholder appraisal and involvement then becomes how to involve river communities in the planning, implementation and adaptive management of a programme of integrated river basin development. Where dams are built for hydropower or irrigation purposes, project compensation and development components for affected people in the river basin would include, for example, funds for planning and implementing small- and medium-scale irrigation projects, thereby increasing the stream of project benefits they receive.

Indeed, one of the most promising means for raising the living standards of rural river communities is through investment in improved, low-technology irrigation opportunities (Comprehensive Assessment of Water Management in Agriculture, 2007). Enhancing downstream agricultural economies can generate a multiplier effect, spurring other aspects of the local economy such as agro-industry, non-farm enterprises and rural towns with associated employment generation (Bhatia et al., 2008). The spread of a number of affordable irrigation technologies for small farms, such as treadle pumps, have raised living standards in rural parts of Bangladesh, sub-Saharan Africa, and elsewhere (Polak, 2008; Postel 1999).

Stakeholder surveys should reveal locations within a river basin that are of critical importance to river-dependent people, e.g. as food sources, as areas for collecting fuel-wood or medicinal plants, for boat-based trade, or for other cultural or spiritual practices. This information should be supplemented with additional ecological information and analysis. This ecological analysis should discern the life cycle and specific water requirements of all plants and animals (including fish) identified as being important to river-dwelling communities, supplemented with similar information for other species of concern from a biodiversity conservation perspective. The summation of this information should emphasise the amount and timing of water flows that must remain in the river to sustain ecological and social values, along with summaries of other habitat requirements such as water temperature and oxygen levels, and nutrient and sediment flows that must be sustained throughout the river system (Krchnak et al., 2009).

This information should then be combined with information on potential dam sites, to explore spatially optimal arrangements of dams that can deliver targeted dam benefits while also sustaining ecological and social values. Figure 7 provides a highly simplified illustration of the optimisation exercise that is required: the two diagrams on the left illustrate the potential conflict between a hydropower development plan and the fisheries in a river basin. In the optimised solution at right, the proposed dams are aggregated in a portion of the basin that is already isolated from fish by an existing downstream dam, thereby obviating the need to build new dams in locations where they would be harmful to fish habitats. Importantly, the operational plan for the existing dam might also need to be modified to provide improved environmental flow releases.

Figure 7. Simplified illustration of a 'spatially optimised' solution.



Illustrations: Courtesy of Jeff Opperman, The Nature Conservancy.

One of the best examples of such spatial optimisation comes from the Penobscot river basin in Maine (US) (Opperman et al., in review). A dam re-licensing settlement between a power company (PPL Corporation) and a coalition of environmental and social interests including the Penobscot Indian Nation, resource agencies, and non-governmental conservation organisations, features the removal of two main-stem dams on the lower Penobscot and improved fish passage at the dams that will remain. Power production will be increased at the remaining dams through various rehabilitation and turbine improvements, such that total hydropower from the basin will be maintained or increase slightly. The effort is projected to considerably expand the proportion of the basin accessible to migratory fish – including the culturally significant Atlantic salmon – and contribute to significant increases in fish populations. The total cost of the Penobscot project has been estimated at US$55 million, with half that amount going to the purchase of the two decommissioned dams by the coalition of environmental and social groups. Obviously, these expenditures could have been avoided altogether through a river basin planning process that would have recognised the potential impact of main-stem dams to the fisheries of this river system, a lesson that should be duly noted by dam planners in the Mekong and other large basins targeted for dam development in coming years.

Step 2. Dam designs and operational plans

If a new dam has been planned in the context of a national, regional, or river-basin planning process as described above, then the intended role of the dam will be understood by all parties, at least at the conceptual level. For instance, the projected power or water-supply yield, or the flood-management function of the dam, should have been specified in the plan. Additionally, important design features of the new dam will also be addressed in the broader plan, such as the need to provide fish passage structures, sediment sluice gates, or environmental flow releases at various dams included in the plan (Krchnak et al., 2009).

As part of the detailed design of each new dam, those design features required to meet goals for the protection of downstream ecosystems and river-dependent communities will need to be explicitly addressed. One of the most important features will be the provision of environmental flow releases adequate to sustain downstream values. The term 'environmental flows' refers to the "quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems" (Brisbane Declaration, 2007). A very large literature has developed on the subject of environmental flows and their implementation (e.g. Postel and Richter, 2003), and environmental assessments have been conducted in more than 70 countries (Tharme, 2003). We cannot provide an overview of this literature here, but we do want to emphasise some key points relevant to addressing social and ecological values.

It is very important that environmental flow needs be assessed by interdisciplinary teams, including natural, physical, and social scientists. The composition of the assessment team should be tailored to include expertise needed to address the full spectrum of ecological and social values identified in Step 1 above. It is also critically important that the intended outcomes for downstream communities be clearly and explicitly stated, such as the intent to sustain fish catches at a specified level. These stated outcomes provide essential information into the process of assessing environmental flow needs; in other words, the environmental flow assessment must explicitly address the flow volume, timing, and quality necessary to sustain downstream social and ecological objectives. While the cost of conducting this type of environmental flow assessment can vary considerably, a typical range is US$100,000-US$500,000 (Richter et al., 2006).

The environmental flow prescription then becomes one of the design objectives to be met by the new dam's structural design and operational plan. The design engineers will need to seek an optimum design that will accommodate all aspects of the environmental flow requirements while meeting other dam operating objectives in the most efficient and cost-effective manner possible (Krchnak et al., 2009). In the case of hydropower dams, special attention must be paid to the sizing and number of turbine-generator units, such that the full range of environmental flow releases can be passed through the turbines and thereby used to generate electricity. This will serve to greatly minimise any hydropower trade-offs associated with integrating environmental flow requirements.

Step 3. Monitoring and adaptive management

In the siting, design, operation, and re-operation of dams, many questions will arise about the likely short- and long-term ecosystem and social impacts, and the degree to which they can be avoided or mitigated. While the best-available expert knowledge and analysis should be employed in every step, dam developers, governments, and stakeholders need to understand that the environmental and social consequences of dam development and operations cannot be predicted with complete certainty. Dam development projects need to be viewed as a continuum that begins with regional or national planning and continues throughout the life of the project. This process must be perpetually informed by monitoring, carefully targeted data collection and research, and further analysis to address new uncertainties or surprises. Therefore, a programme of monitoring, evaluation, and adjustment – commonly referred to as 'adaptive management' – should be fully and explicitly integrated into any dam development or re-operation plan so that management approaches can be continually modified in light of increased understanding or changes in human and ecosystem conditions.

CONCLUSION

In this paper we have described the ways that dams have disrupted the livelihoods and well-being of hundreds of millions of river-dependent people around the globe. We have developed the first global estimate of the number of 'potentially affected' people, based on a new database of more than 120 river-specific case studies and a GIS analysis of populations located downstream of the ~7000 largest dams. We conservatively estimate that 472 million people have been affected by these dams.

While some lending institutions, governments, and companies in the dam industry have taken important steps to correct the social inequities too often associated with dam projects, the overall response has been far too slow, and inadequate. Here we have highlighted three steps that if implemented fully would help rectify the ecological and social costs and inequities that have resulted from dam development projects. While each of these steps has been promoted in the WCD Report and elsewhere, our discussion of these three 'best practices' goes into greater specificity than what was presented in the WCD Report. We have also made the case that these corrective measures are not necessarily expensive and can be usually implemented without compromising the primary goals and benefits of dam projects, and in many cases can increase project benefits by ensuring that downstream people participate in the benefit-sharing process. All such measures will be far easier, less expensive, and more politically acceptable if they are integrated into dam development plans at the very earliest stage.

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