



Hydropower Development and Ecosystem Services in Central America

Elizabeth P. Anderson

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Acronyms

ICE	Institute of Electricity (Costa Rica)
MW	Megawatt
PES	Payment for Environmental Services

Abstract

The Neotropical region, consisting of Central and South America and parts of the Caribbean, is drained by a diversity of river systems that harbor a large part of global species richness in freshwater organisms and provide critical goods and services to millions of people. For example, of the world's roughly 12,000 species of freshwater fishes, an estimated 50 percent are found in Neotropical rivers and lakes; these numbers correspond to approximately 20–25 percent of all fishes, considering both freshwater and marine species.¹ People's lives and livelihoods are often intimately dependent on freshwater ecosystems: their fisheries provide an important source of protein and income, rivers are critical or often the sole routes for transportation and communication, and much of the region's cultural diversity has developed along river corridors in wilderness areas of the Amazon and the Caribbean lowlands of Central America.

Use of rivers for hydropower generation is a key freshwater ecosystem service that has been gaining in importance, extent, and impact over the past 25 years. Dozens of dams have been constructed on Neotropical rivers since the 1980s, and hundreds more are receiving consideration, are in advanced stages of planning, or are under construction.² Hydropower is an important component of development and helps in meeting electricity needs, but it often also brings myriad environmental and social changes that can affect freshwater ecosystems and their services.

The case of Central America—in this paper meaning Belize, Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, and Panama—illustrates the importance of rivers from both ecological and socioeconomic perspectives and also some of the trends of increasing hydropower development currently playing out in the Neotropics.³ Central American rivers contain hundreds of characteristic species of fishes and shrimps, including many migratory species that depend on a natural flow regime and upstream-downstream connectivity for survival. Human populations derive most water for consumptive uses from surface waters, and

¹ Reis et al. 2003.

² Anderson et al. 2006b; Finer and Jenkins 2012.

³ Anderson et al. 2006b.

rivers provide a source of food, income, and building materials, serve as transportation routes, and have strong linkages to the cultural identity of rural people. Hydropower is a critical source of electricity across the region, and dams are seen as important to future economic stability and development in Central America. However, existing dams in Central America have been linked to declines in migratory and sensitive fish species, to the compromise of other ecosystem services, and to negative impacts on people's health and well-being.⁴

This paper provides an overview of the characteristics of Central American rivers and related freshwater ecosystem services, discusses trends in hydropower development and known environmental and social consequences, and Offers suggestions for finding a balance between hydropower and the protection of other freshwater ecosystem services, based on experiences from the region.

⁴ McCully 1996; Bonta 2004; Anderson et al. 2006a; McLarney et al. 2010.

1. Rivers of Central America

Central America is one of the 34 regions of the world with the highest level of species richness and endemism, and it consequently has been the focus of much ecological research and internationally supported initiatives for conservation over the past 50 years.⁵ Terrestrial ecosystems, particularly tropical forests, have garnered most of the conservation and ecological research community's attention. In fact, much of the current global understanding of tropical ecosystems and models for their conservation comes from studies conducted in Central America, especially Costa Rica. Conversely, the region's freshwater environments remain relatively understudied, and freshwater ecosystems are just beginning to be considered more explicitly in conservation planning.⁶ This is a trend not unique to Central America.⁷

Recent attempts have tried to understand the ecological structure and function of Central American freshwater ecosystems within a nested framework that considers ecoregions, ecological draining units (i.e., a river basin), lentic and lotic ecological systems (i.e., individual lake or river), and freshwater species.⁸ The highest geographic level of this framework, the freshwater ecoregion, is defined by patterns of climate, geology, or evolutionary history rather than just basin boundaries.⁹ For Central America, 11 freshwater ecoregions have been defined, extending from southern Chiapas in Mexico through the Darien of Panama (see Table 1.)¹⁰

In terms of riverine, or lotic, ecosystems, some general characteristics can be identified across the isthmus. Tropical rivers of Central America are highly heterogeneous systems, ranging from fast-flowing mountain torrents in areas of high relief to slow-moving rivers that meander through lowland environments. Mountain chains running longitudinally through much of the isthmus divide Central America into Caribbean and Pacific slopes that experience different climatic patterns, particularly in terms of precipitation. These differences are reflected in the hydrologic regimes of rivers: many Caribbean slope rivers drain more humid landscapes and tend to be more aseasonal, while Pacific slope rivers tend to experience marked wet and dry seasons, with corresponding periods of high and low flows. Relative to rivers in neighboring North and South America, the narrowness of the isthmus means that Central American rivers are

5 Myers et al. 2000; Conservation International 2007.

6 Paaby 2008.

7 Abell et al. 2007.

8 TNC 2009.

9 Ibid.

10 Ibid.

shorter in length, carry a substantially lower volume of water as they drain smaller basins, and generally are closely connected to marine environments.

Freshwater species take advantage of the array of habitats available in Central American rivers. The region's freshwater and semi-aquatic fauna includes wading and riparian birds, mammals, reptiles and amphibians, fishes, and invertebrates, including many insects and crustaceans. These species can be obligate freshwater organisms (e.g., fishes), be freshwater specialists, or have critical life cycle stages during which they depend on freshwater habitats.

Freshwater fish species richness is much lower in Central America than in South America, in part because of the region's more recent origin.¹¹ Roughly 530 species of fish are known to inhabit the Central American region.¹² On the basis of colonization routes from North and South America, Central America was historically divided into four different ichthyological provinces: Usumacinta (southern Mexico to the Coco River, Honduras-Nicaragua border, Caribbean slope), Chiapas-Nicaraguense (southern Mexico to Costa Rica, along Pacific slope), San Juan (Coco River to central Panama, Caribbean slope), and Isthmian (southern Pacific slope of Costa Rica through to Panama-Colombia border, both slopes).¹³ However, these divisions and much of what is known about Central American freshwater fishes came from studies conducted in the middle of the last century.¹⁴ Recently there has been a marked increase in research aimed at filling knowledge gaps of distribution patterns of freshwater fishes, and further divisions of Central America into smaller ichthyological regions have been proposed.¹⁵

Finally, many Central American freshwater species, particularly fishes and shrimps, are diadromous, meaning that they exhibit some form of migratory behavior or need access to saltwater at some stage in their life cycle.¹⁶ The survival of migratory species depends on unimpeded movement along river channels between upland freshwater habitats and coastal areas.

Scientific, or even quantitative, information on the socioeconomic importance of Central American rivers is perhaps more limited than ecological data. People in Central America depend on rivers for multiple ecosystem services (e.g., water supply, transportation, food, waste assimilation), yet to the best of our knowledge a systematic approach to understanding this dependence and the value of these does not exist. Following the Millennium Ecosystem

¹¹ Reis et al. 2003.

¹² TNC 2009.

¹³ Bussing 1976.

¹⁴ Miller 1966; Bussing 1976.

¹⁵ Smith and Bermingham 2005; Matamoros et al. 2009; Esselman and Allan 2011; Matamoros et al. 2012.

¹⁶ McLarney et al. 2010; Esselman and Allan 2011; Lorion et al. 2011; Nordlie 2012.

Assessment, freshwater ecosystem services can be grouped into four main categories: provisioning, supporting, regulating, and cultural.¹⁷ Examples of provisioning services of Central American rivers include water supply for domestic, industrial, and agricultural uses; fisheries; and aquatic plants and bed sediments that provide building materials. Supporting and regulating services include transportation, flood control, and waste assimilation. The cultural services linked to Central American rivers include recreation, cultural identity, and rivers as historical reference points.

An important consideration here is that with rivers in an ecologically intact state, many of the ecosystem services provided by Central American rivers come at little or no economic cost to society. When rivers have been degraded or altered, however, and the ability of a river to provide an ecosystem service has been compromised, people must consider alternatives, which often involve significant economic costs and the need for new infrastructure. An example here would be the provisioning ecosystem service of water supply for domestic, industrial, and agricultural uses. Water quality of rivers in a near-natural state could mean minimal or no need for water treatment prior to use; in rivers that drain urban or deforested landscapes or that receive substantial inputs from point source effluents, water quality may be compromised to a point where potentially costly treatment processes are necessary prior to use for other human activities. A large body of research and new tools have recently aimed to place economic value on freshwater ecosystem services in Latin America and to assess the cost to society when rivers can no longer provide these services as a result of alteration or degradation.¹⁸

Since the early 1980s, hydropower has emerged as one of the most important ecosystem services provided by Central American rivers. High annual precipitation (in excess of 4 meters in some areas), particularly along the region's Caribbean slope, guarantees sufficient water for electricity generation, and high relief increases the amount of power that can be generated from available water. Regionally, hydropower accounts for approximately 50 percent of net electricity generation and 42 percent of total installed generation capacity, although the relative importance of hydropower varies by country.¹⁹ (See Tables 2 and 3.) Costa Rica is the regional leader in terms of installed generation capacity and dependence on hydropower, which accounted for approximately 73 percent of net electricity generation in that country and 62 percent of installed

¹⁷ Millennium Ecosystem Assessment 2005.

¹⁸ See www.naturalcapitalproject.org and references within.

¹⁹ UN-CEPAL 2012.

capacity in 2011.²⁰ A distinguishing feature of hydropower relative to some other freshwater ecosystem services (e.g., recreation, cultural) is that the related ecosystem service is typically not produced and used in the same place, but rather benefits distant users. Additionally, because hydropower generation results in alteration of rivers and the natural flow regime, hydropower often compromises the availability or quality of other freshwater ecosystem services both upstream and downstream.

2. Extent and Trends of Hydropower Development in Central America

Central America has experienced a proliferation of hydropower dams in recent years, a trend that began with the construction of a few large dams in the 1980s (e.g., Arenal Dam in Costa Rica, El Cajon in Honduras, and Chixoy in Guatemala), that accelerated with the privatization of electricity generation in the 1990s, and that has continued in the current century. Population growth, an increase in rural electrification, and rising electricity consumption (estimated at 4.2 percent regionally in 2011)²¹ are important drivers of hydropower development in Central America. The reduced availability of domestic fossil fuel sources, as well as the natural features of the Central American landscape, particularly topography and climate, lend themselves to hydropower development as a preferred method of electricity generation on the basis of cost and opportunity for domestically produced energy.

Much of Central America's hydropower potential remains untapped. As of 2011, installed generation capacity of hydropower dams in Central America was estimated at around 5000 megawatts (MW). Of those, hydropower dams in Costa Rica accounted for roughly 1644 MW, followed most closely by Panama (1294 MW) and Guatemala (902 MW), and trailed by Nicaragua (105 MW) and Belize (25 MW). (See Table 3.) Regionally, installed hydropower generation capacity nearly doubled from 1990 to 2010.²² (See Table 2.) During the 1990s, Costa Rica alone constructed around 30 new hydropower plants, many of which were made possible by legislation passed at the start of the decade that partially opened electricity generation to the private sector.²³ In 2005, a compilation of proposed hydropower developments in Central America, which included projects at stages from investment opportunities to feasibility,

²⁰ Ibid.

²¹ Ibid.

²² Ibid.

²³ Anderson et al. 2006b.

documented close to 400 potential dam projects amounting to an aggregate 16,165 MW of installed generation capacity.²⁴

According to recent statistics from the UN-CEPAL (2012), a net 419 MW of installed capacity was added by large hydropower projects in 2011, including the Changuinola and Bajo de Minas projects in Panama and the Pirris Dam in Costa Rica. An additional ~130 MW of installed capacity was contributed by numerous small and medium-sized hydropower projects in Panama, Guatemala, and Nicaragua in 2011. Most of these projects were developed by private companies.²⁵ Expansion plans for the period 2012–2027 project many new hydropower developments in Central America, including large dams as well as small and medium-sized projects. In particular, extensive hydropower development is under way or planned for Panamanian rivers during 2012–2014.²⁶

Hydropower developments in Central America come in various sizes, types, and modes of operation. While numerous classification systems for dams based on these factors exist,²⁷ most commonly there are two kinds of hydropower projects in the region: in-channel large storage reservoirs with dams that are more than 15 meters high and smaller, run-of-river projects with water diversion dams less than 15 meters high and with off-channel reservoirs or no water storage capacity. In some cases the installed capacity (in megawatts) of a hydropower project is related to the size of its dam, with larger, storage-type projects that are able to generate more electricity having also larger dams and smaller, run-of-river projects having smaller dams as well as lower installed capacity (e.g., <50 MW).

However, the use of installed generation capacity (MW) as a proxy for dam size or type can be misleading. Some dams in Central America—for instance, the 7.3 MW Chalillo Dam in Belize—have comparatively large in-channel reservoirs relative to the amount of installed generation capacity; others—for instance, the 90 MW Toro Hydroelectric Complex in Costa Rica—operate by means of multiple water diversion dams, with a small volume of water storage relative to installed generation capacity. The choice of size, type, and mode of operation of a hydropower development depends on many variables, including the natural features of the landscape at the dam site (e.g., topographic relief, river flow, annual precipitation); the economics, electricity rates, and available funds for the project; whether the dam is privately or

²⁴ Burgues Arrea 2005.

²⁵ UN-CEPAL 2012.

²⁶ CEAC 2012.

²⁷ World Commission on Dams 2000.

publicly owned and operated; and the generation goals of a project in terms, for example, of peak load versus other ancillary services it might be designed to provide.

Certain river basins or areas of Central America have been focal points for hydropower development, meaning that they have disproportionately high numbers of existing or proposed dams relative to other basins. One such area that has been heavily targeted for hydropower development is the Caribbean slope of Costa Rica and Panama. The San Carlos and Sarapiquí Rivers, both tributaries of the San Juan River in Costa Rica, have seen a dramatic increase in damming in their basins, with approximately 30 hydropower plants constructed over the past 25 years and more projects under consideration.²⁸ On the Reventazón River, which also drains to the Caribbean Sea, the Costa Rican Institute of Electricity (ICE) is currently constructing its fourth dam, Reventazón (305 MW), on that system (Rio Macho, Cachi, and Angostura are existing projects); several private hydropower projects are either in operation or under construction in the Reventazón Basin as well (e.g., La Joya, Rio Lajas, Tuis, Birris, Torito).²⁹ Similarly, several basins that drain the La Amistad World Heritage Site in Costa Rica and Panama recently have been targeted for hydropower development; these include the Rio Banano, La Estrella, Sixaola, and Changuinola basins on the Caribbean slope and the Terraba, Chiriqui, and Chiriqui Viejo basins on the Pacific slope.³⁰

3. Understanding the Ecological and Social Consequences of Flow Alteration in Central America

An extensive body of literature documents the effects of hydropower dams on river ecosystems and on nearby human populations,³¹ including an increasing number of studies that examine dams in tropical regions.³² A few trends emerge from this literature. First, hydropower projects vary in the magnitude, extent, and reversibility of adverse environmental and social effects. For example, large storage dams often flood large areas, turning flowing-water environments into more lake-like systems. This often requires resettlement of human populations, and the displaced populations are often indigenous people who inhabit wilderness areas to which they have strong

²⁸ Anderson et al. 2006b; Anderson et al. 2008.

²⁹ IDB 2012.

³⁰ McLarney et al. 2010.

³¹ World Commission on Dams 2000; International Hydropower Association 2010.

³² Pringle et al. 2000; Anderson et al. 2006a, 2006b.

cultural connections.³³ Smaller, run-of-river hydropower projects can result in significantly reduced flow over several kilometers of river channel between the water diversion site and the turbine house. These flow reductions can make the river unusable for transportation or recreation or may be linked to declines in fish or other aquatic species.

Second, different kinds of environmental and social impacts may occur during construction, early operation, and long-term operation of a hydropower project. An example here would be a dam that floods a forested area and that requires human resettlements during the construction phase, that emits high amounts of methane and carbon dioxide from decomposing vegetation in its reservoir during early operation, and that results in the extirpation of native fishes or shifts in composition of fish species assemblages to favor more lentic-adapted species over the long term.

Third, related infrastructure, like access roads and power transmission lines, may have other environmental and social impacts on a dam site. In forested landscapes, these related infrastructural developments sometimes spark deforestation or forest degradation by providing new points of access.

Finally, many facets of a river's flow regime—magnitude, timing, duration, frequency, and rate of change—influence the structure and function of freshwater ecosystems and their ability to provide key ecosystem services to human populations.

While hydropower developments can be of different types and sizes, virtually all alter one or more of these facets of a river's flow regime. Rather than list all the different ecological and social effects of dams, this discussion of hydropower development in Central America focuses on flow alteration and the presence of dams as barriers as among the most important potentially negative consequences of hydropower—and a characteristic of nearly all dams.

Flow acts as a master variable in rivers, shaping physical habitat and providing connectivity, influencing the composition of species that inhabit fluvial systems, and selecting for life histories of aquatic species.³⁴ The variability inherent in a river's natural flow regime—base flows, low flows, pulse flows, high flows, flood flows, when they occur and how long they last—is ecologically very relevant. For example, base flows or low flows often provide habitat stability over long periods; these same periods may be when reproduction of fishes occurs and stable habitat is needed for nursery areas. Pulse flows or high flows flush sediment from

³³ Finley-Brook and Thomas 2010.

³⁴ Poff et al. 1997.

interstitial spaces, creating or maintaining habitat for fluvial species like macroinvertebrates. Flood flows form river channels and can act as a kind of reset event that eradicates exotic species or connects river channels to floodplain areas. Additionally, flow events can serve as cues for migratory species to move upstream or downstream for spawning or feeding.³⁵ Freshwater inflows, and the sediments, nutrients, and organic matter that they transport, are critical to coastal and marine ecosystems, particularly in landscapes like Central America, where rivers are short and there are strong connections between freshwater and coastal systems.

Alterations to river flow and losses in riverine connectivity that occur as a result of hydropower development (or other factors) disrupt flow-ecology linkages, with negative consequences for freshwater ecosystems. Recent research from Central America provides evidence of these consequences, particularly as related to persistence of freshwater species. Studies of fishes along a four kilometer de-watered reach of river downstream from a small, run-of-river hydropower plant in Costa Rica suggested that flow alterations favored opportunistic life history strategists (e.g., *Poecilia*, *Rhamdia*, *Astyanax*) over periodic and equilibrium life history strategists (e.g., *Agonostomus*, *Archocentrus*, *Astatheros*, *Theraps*)—in other words, favoring the persistence of fish species more tolerant of wider ranges of environmental conditions over more-sensitive species.³⁶ Using studies from dammed rivers in Puerto Rico as a proxy, attempts to predict the consequences of flow alteration and the existence of dams as barriers have suggested that dams proposed for the La Amistad region shared by Costa Rica and Panama will result in a near-total extirpation of migratory fishes (e.g., *Anguilla*, *Agonostomus*, *Joturus*, *Awaous*, *Sicydium*, *Gobiomorus*) and shrimps (e.g., *Macrobrachium*, *Atya*, *Micratya*, *Potimirim*) upstream from dams.³⁷ Fish surveys in tributaries of Lake Arenal and upstream from dams on the Reventazón and Puerto Viejo Rivers in Costa Rica suggest that diadromous freshwater mullets, *Agonostomus monticola* and *Joturus pichardi*, may have disappeared following dam construction.³⁸

Flow alterations have potentially wide-ranging consequences for human populations as well. Much of the social science research on tropical dams worldwide has focused on the problems associated with resettlement (particularly of indigenous people), the increased incidence of disease following the construction of reservoirs, or community resistance to dam

³⁵ Ibid.

³⁶ Anderson et al. 2006a.

³⁷ McLarney et al. 2010.

³⁸ Anderson et al. 2006b; McLarney et al. 2010; Lorion et al. 2011.

projects.³⁹ Flow alterations also compromise the availability and quality of freshwater ecosystem services. In a Central American context, all categories of freshwater ecosystem services—provisioning, supporting, regulating, and cultural—have been at issue with hydropower development.

In terms of provisioning services, surface waters in Central America—and mainly rivers and streams—are the primary source of water for human activities. Flow alterations downstream from dams, especially large, storage projects, can affect water quality and make river water unfit for other human uses. Freshwater fisheries production is an important provisioning service provided by many tropical rivers, often guaranteeing a source of protein and income for rural or indigenous peoples populations in lowland areas. By affecting the persistence of freshwater fish species, often those prized in fisheries, dams and associated flow alterations decrease access to fisheries resources.⁴⁰

In terms of supporting and regulating services, multiple studies have documented the importance of Central American lowland rivers as primary communication and transportation routes for human populations, such as the Tawaka and Miskito people who inhabit the lower Patuca River basin in Honduras.⁴¹ Other rivers draining the Caribbean lowlands have historically been major thoroughfares as well; an example is the San Juan-Sarapiquí River system in Costa Rica, which provided a main route of access between the Caribbean and Costa Rica's central valley until the mid-1960s.⁴² More recently, high-gradient rivers in Central America have been used for white-water rafting. In Costa Rica, where environment-based tourism provides one of the country's largest sources of economic revenue, roughly 10 percent of visitors claim to have gone on rafting trips.⁴³ Flow alterations, particularly reductions in flow, can compromise river navigation downstream from dams and therefore alter people's ability to rely on rivers as primary transportation routes or sources of environmental tourism-related income.⁴⁴

In terms of cultural services, rivers throughout Central America provide deep linkages to the identity of local people and important centers of recreation, particularly in rural areas. On Sundays and holidays, people frequent river banks and swimming holes in deep river pools, and many restaurants are located in areas with river views. Flows downstream from hydropower

³⁹ McCully 1996; Bonta 2004; Finley-Brook and Thomas 2010; Naiman and Dudgeon 2011.

⁴⁰ Hoeinghaus et al. 2009.

⁴¹ Esselman and Opperman 2010.

⁴² Butterfield et al. 1994.

⁴³ Fletcher 2010.

⁴⁴ Esselman and Opperman 2010.

dams can be somewhat unpredictable, rising in response to peak generation periods as opposed to rainfall events, and therefore use of rivers for recreational purposes is often compromised for safety reasons. For example, along the Puerto Viejo River on Costa Rica's Caribbean slope, signs posted in riparian towns downstream from a small hydropower plant warn of the potential of rapid rise of river flow and urge people not to swim in the river or linger on its banks (author's observation). Similarly, some large ICE-run projects in Costa Rica publish ads in the newspaper when cleaning sediments from reservoirs to warn neighboring human populations of sudden changes in stream flow (M. Rojas, personal communication).

4. Considering Hydropower in Central America against a Backdrop of Climate Change

Climate change is altering the discourse on the costs, benefits, and ecological and social impacts of hydropower projects in multiple ways. Globally, several models and scientific studies have projected significant changes to runoff in many of the world's river basins as a consequence of warming temperatures and alterations in historical patterns of precipitation, especially decreases in total annual rainfall.⁴⁵ The cumulative effects of warming and altered patterns of precipitation on the landscape are integrated by river basins and can lead to changes in the intensity, duration, and frequency of extreme events like droughts and floods. Climate-related changes are likely to affect the availability of water for hydropower generation, especially in basins where reductions in precipitation are projected, and may even affect the safety of hydropower projects, particularly in basins with predicted changes to flooding regimes in the future.⁴⁶

Central America is considered one of the most vulnerable regions to climate change and has been recognized as a potential "climate change hotspot" on the basis of the magnitude of projected changes in temperature and precipitation relative to other areas.⁴⁷ According to the Intergovernmental Panel on Climate Change, by 2100 Central America is likely to experience warming temperatures (1.8–5.0°Celsius annual mean warming; median 3.2°Celsius), an increased number of dry days, and an increased frequency of more intense precipitation and extreme events. There is still some uncertainty about what will occur in terms of total annual precipitation, but general circulation models suggest a reduction, especially along Central

⁴⁵ Palmer et al. 2008; Vorosmarty et al. 2010.

⁴⁶ Maurer et al. 2009.

⁴⁷ Giorgi 2006; Maurer et al. 2009.

America's Pacific slope.⁴⁸ Models downscaled to the Central American region also suggest that substantial reductions in precipitation will occur on the Pacific slope, as well as along the Caribbean regions of Costa Rica and Panama. These downscaled models predict the magnitude of warming in the wet season to be more than 4°Celsius and between 3 and 4°Celsius in the dry season over most of Central America.⁴⁹

Changes in water availability, particularly shortages of water as a consequence of reductions in precipitation and therefore river discharge, could affect hydropower generation in the future. Modeled current and future discharges, using the HadCM3 climate change model and A2 scenario, predict that several Central American rivers will see large reductions in annual discharge by the 2050s compared with historical hydrologic records from the period 1960–1990; among these rivers are the Coco (predicted –69.8 percent change in annual discharge), the Patuca (–72.0 percent change), and the San Juan (–72.6 percent).⁵⁰

A recent analysis from the tri-national Lempa River Basin (Honduras, Guatemala, and El Salvador)—the location of two hydropower facilities that supply power to El Salvador (Cerron Grande and 15 Septiembre)—illustrates in a quantitative way the potential influence of climate change on runoff and therefore river inflow to reservoirs.⁵¹ Models scaled to the Lempa River Basin project a warmer (average 1.9°–3.4°Celsius, under A2 and B1 scenarios, respectively) and drier (10.4–5.0 percent drier, under A2 and B1 scenarios, respectively) future for the basin. Translating these projections into low-flow frequency—a determinant of firm power availability or the electricity that a hydropower facility can supply in dry years—indicates that hydropower projects in the Lempa River Basin could experience a decrease in generation capacity on the order of 33–53 percent near the end of this century. On a shorter timescale, these analyses call for water managers to prepare for at least a 13 percent reduction in reservoir inflow in the coming decades.⁵² Few published analyses like that completed for the Lempa River Basin exist for river basins in Central America. Nevertheless, these kinds of studies are critical for understanding the viability of existing and future hydropower projects under different climate change scenarios.

⁴⁸ Cifuentes 2010; Karmalkar et al. 2011.

⁴⁹ Karmalkar et al. 2011.

⁵⁰ Palmer et al. 2008.

⁵¹ Maurer et al. 2009.

⁵² Ibid.

A further, interesting intersection between climate change and hydropower development merits mention here. Climate change and its associated impacts on river flows are likely to affect dams in the future, as illustrated by the Lempa River case. At the same time, policies to address climate change through decreased use of fossil fuels may place increased emphasis on hydropower dams as a component of future energy strategies, since hydropower is often viewed as a clean source of electricity. The Clean Development Mechanism under the Kyoto Protocol in particular has been an incentive for hydropower development in tropical developing countries in an era of increased concern about climate change.⁵³

5. Finding a Balance

Several good examples of best practices are emerging from Central America in response to the challenge of balancing hydropower development and the protection of other freshwater ecosystem services. This final section discusses these examples within the framework of five recommendations for a move toward more sustainable hydropower in the region.

6. Consideration and Implementation of Internationally Developed Criteria for Site Selection and Operation of Hydropower Projects

The more than 48,000 large dams and the estimated >800,000 smaller dams worldwide offer opportunity for improving our understanding of the factors that can exacerbate or mitigate the negative environmental and social consequences of hydropower dams.⁵⁴ The World Commission on Dams represented a global effort to try to elicit lessons from more than a century of dam building, and this process culminated in the publication of a series of recommendations for more sustainable hydropower development.⁵⁵ The International Hydropower Association's recently developed Hydropower Sustainability Assessment Protocol is a framework designed to guide incorporation of sustainability concerns on the technical, environmental, social, and economic aspects of dams and the integration of these four aspects into the life cycle of a dam project from development to operation.⁵⁶

⁵³ McCully 1996; Fletcher 2010.

⁵⁴ McCully 1996; World Commission on Dams 2000.

⁵⁵ World Commission on Dams 2000.

⁵⁶ International Hydropower Association 2010.

Similarly, syntheses of information on impacts of dams in tropical regions, including Latin America, have led to development of criteria for good and bad dams⁵⁷ or to specific guides of best practices for hydropower projects. (An example of the latter is the *Guía de Buenas Prácticas Ambientales para Pequeños Proyectos Hidroeléctricos* for Honduras, recently produced by a consortium of institutions.) These criteria are designed to identify where the potential for environmental and social impacts could be so unfavorable as to undermine the electricity benefit of a hydropower project or could be extremely difficult or impossible to mitigate. Additionally, experience from many hydropower projects, primarily in the temperate zone, has shown how structural adjustments can be made to dams or incorporated into design in order to release compensation flows downstream or maintain some degree of longitudinal riverine connectivity.

An obvious suggestion for Central America as related to improving the sustainability of new hydropower developments is to consider and implement these internationally recognized criteria (see Table 4). For example, for many projects the single most important measure toward more environmental and socially sustainable hydropower is good site selection. For large dams, “good” hydropower projects might include, among others, the following characteristics: a small reservoir surface area and little flooding of tropical forests, limited loss of natural habitats, location on a river not recognized as having high freshwater species richness or endemism at risk, many downstream tributaries that aid in restoring flows, no need for resettlement of human populations, and low incidence of tropical diseases.⁵⁸ For smaller, run-of-river dams, “good” hydropower projects might have a low-head dam at the water diversion site that leaves the river channel partially unblocked, very little or no distance of de-watered river between the dam and turbine house, and a power generation schedule that is somewhat constant (e.g., doesn’t release unnatural peak flows).⁵⁹

Some caution is urged when applying lessons or approaches developed outside of Central America or of tropical regions. Here, the concept of fish ladders provides a case in point. Fish ladders developed for temperate fish species (e.g., salmon) have often been simply exported as a management strategy to tropical dams without adequate consideration as to whether they would actually facilitate passage of tropical species or be ecologically effective. Recent research indicates that many fish passage structures at dams in Brazil are ineffective or, ironically, are

⁵⁷ Goodland et al. 1993; Ledec and Quintero 2003.

⁵⁸ Ledec and Quintero 2003.

⁵⁹ Anderson et al. 2006a.

contributing to regional fishery collapse.⁶⁰ To remedy this situation in Brazil and prevent it in other places, it has been recommended that fish passage structures consider the location of critical habitats and facilitate movement in both upstream and downstream directions. Additionally, their effectiveness should be evaluated in terms of whether they maintain viable fish populations as a replacement for the typical measure of successful fish ascension upstream.⁶¹

7. Development of Central American Datasets and Frameworks for Environmental Flow Assessment and Implementation of Recommended Flows

Ideally, a sustainable hydropower project should protect the aspects of the flow regime that are most important to ecosystems and to society. The term environmental flow refers to the quantity, quality, and timing of fresh water needed to sustain aquatic and terrestrial ecosystems and the related ecosystem services on which people depend.⁶² Environmental flow assessment—a process by which the flow needs of ecosystems are estimated and corresponding recommendations for water allocation to ecosystems are developed—is quickly becoming standard practice in water resources management worldwide.⁶³ This trend has extended to Neotropical countries most notably in the past decade, with many countries revising water-related legislation to include guidance as related to environmental flows or engaging in environmental flow assessments for individual rivers.⁶⁴

In general, approaches to assessing environmental flows fall into four main categories: (i) hydrology-based approaches (e.g., Tennant method), which express recommended flows usually as a portion of annual or monthly discharge; (ii) hydraulic-rating approaches, which link flows to hydraulic conditions like depth, velocity, or wetted perimeter; (iii) habitat simulation approaches (e.g., IFIM/PHABSIM), which identify the amount of suitable or ideal habitat available during different flows, usually for a target species of fish, and make flow recommendations based on that species' habitat needs; and (iv) holistic approaches (e.g., BBM, DRIFT), which aim to consider the multiple uses of rivers, and their ecological and social importance, and to make flow recommendations within a more integrated context.⁶⁵

⁶⁰ Pompeu et al. 2012.

⁶¹ Ibid.

⁶² Dyson et al. 2003; Poff et al. 2010.

⁶³ Naiman et al. 2002; Tharme 2003.

⁶⁴ Scatena 2004; Diez and Burbano 2006; Diez and Ruiz 2007; Anderson et al. 2011.

⁶⁵ Tharme 2003.

In Central America, examples from Honduras and Costa Rica illustrate the challenges and opportunities for determining and implementing environmental flow recommendations. During 2006–2008, a collaborative project between the National Electric Energy Company of Honduras, The Nature Conservancy, local stakeholders, and scientific experts aimed to develop environmental flow recommendations to be incorporated into the design and operation of the then-planned Patuca 3 hydropower project on the unregulated Patuca River.⁶⁶ The Patuca, the third longest river in Central America at 465 km, harbors diverse assemblages of aquatic species and meanders through three national protected areas inhabited by the indigenous Miskito and Tawahka peoples, with populations of roughly 6,400 and 1,100, respectively, in the lower Patuca Basin.⁶⁷ Both groups depend on the Patuca River as a source of food, agriculture, building materials, and drinking water. But one of the freshwater ecosystem services most at risk of compromise with construction of Patuca 3 was the communities' exclusive reliance on the river as a transportation route for trade of crops, livestock, and forest products and for communication between villages.⁶⁸

Very limited scientific data on the hydrology and ecology of the Patuca River presented a challenge to the environmental flow assessment. However, the project team benefited greatly from the indigenous peoples' traditional ecological knowledge of the river. When combined with hydrologic analysis and input from scientific experts, this traditional ecological knowledge was used to elicit relationships between the river's flow regime and fish and aquatic organisms; between flow and terrestrial resources, human communities, and riparian forests; and between flow and channel morphology. These elicited relationships, plus a separate consideration of critical points for river navigation, provided the basis for environmental flow recommendations for the Patuca River for the reach downstream of Patuca 3.⁶⁹

Although the Patuca study exemplifies some of the opportunities and non-traditional sources of data that can be used for environmental flow assessments, it also illustrates the need for consideration of dams and environmental flow assessments within a basin context. Additional dams planned for areas downstream of the Patuca 3 site could make environmental flow recommendations difficult to implement unless these recommendations also consider these future projects. Further, simply conducting an environmental flow assessment does not necessarily

⁶⁶ Esselman and Opperman 2010.

⁶⁷ McSweeney 2002.

⁶⁸ McSweeney 2002, 2004.

⁶⁹ Esselman and Opperman 2010.

mean that a dam project should move forward; ecological and social concerns at a basin scale may not be able to be sufficiently mitigated through implementation of an environmental flow regime, as may be the case in the Patuca River Basin.⁷⁰

In Costa Rica, since the early 2000s several different groups have worked toward development of environmental flow recommendations for multiple rivers. One of the first attempts at establishing an environmental flow downstream from a dam came from a private hydropower plant on the Puerto Viejo River on the country's Caribbean slope, where a "compensation flow" of 5–10 percent of average annual discharge was built into the design of the dam, which operates as a water diversion / run-of-river type hydropower facility. Ecological research conducted at the dam site and within a ~4 km de-watered reach between the dam and the turbine house suggested that the quantity and timing of the compensation flow could sustain a subset of fish species—primarily those that were opportunistic breeders or habitat generalists—but was not likely to be sufficient for fishes with more complex reproductive requirements (e.g., parental care in Cichlids) or for migratory species.⁷¹

Similar research on Costa Rica's Tempisque River identified two indicator species, a Cichlid fish (*Parachromis dovii*) and a crocodile (*Crocodylus acutus*), each with part of their life cycle critically dependent on river flows.⁷² *P. dovii* is known to spawn in caves or trunks in deep pools within the river channel; the fish's size requires minimum pool depths of approximately 1 meter for spawning. Likewise, crocodiles in the Tempisque depend on sand banks, aquatic vegetation, and minimum depths of around 1.1 meters for reproduction. Using hydraulic models, these depths can be linked to corresponding river flows and used to recommend the quantity of water needed in a river during periods of reproduction of these two species.⁷³

At the national level, the Costa Rican Institute of Electricity, responsible for much of Costa Rica's hydropower development, recently has developed a hybrid approach to estimating environmental flows downstream from dams, on the basis of case studies and field data collection from the Savegre River on the Pacific slope and the Reventazón River on the Caribbean slope. Known as the RANA-ICE, the methodology and accompanying software program combine hydrological analyses with experts' professional judgments, biological

⁷⁰ Ibid.

⁷¹ Anderson et al. 2006a.

⁷² Jimenez et al. 2005.

⁷³ Ibid.

response modeling, socioeconomic water needs, and scenario identification in an attempt to integrate natural and social science for determining minimum acceptable river flows.⁷⁴

These cases from Honduras and Costa Rica are just a few of the attempts in the region and the methods used to assess and implement environmental flows for river reaches downstream from dams. Given the extent of hydropower development across Central America, there is both a need to share lessons and data from these individual studies and a need to develop frameworks for environmental flow assessment and implementation within a Central American context.⁷⁵ For example, data limitation presents a challenge for many Central American rivers. The case of the Patuca River in Honduras shows the value of traditional ecological knowledge and the use of experts' professional judgment in the absence of extensive ecological and hydrological information for development of environmental flow recommendations.⁷⁶ The Patuca example also illustrates how key ecosystem services, in this case rivers as transportation routes, can be considered in flow management plans downstream from dams.

In Costa Rica, many environmental-flow initiatives have included research on the flow-ecology relationships of freshwater biota and have considered genera that are distributed in many Central American rivers (e.g., *Parachromis*, *Crocodylus*, *Agonostomus*). Findings from these studies may help inform development of environmental flow recommendations or river management strategies in other parts of the region or help identify species that can be used as indicators of flow alterations in Central American rivers.

Finally, all these cases underscore the need to take a holistic approach in the development of environmental flow recommendations. Ideally, dams should function in a way that can somehow mimic the natural variability of a river, and the array of freshwater ecosystem services provided by rivers should be considered explicitly in flow management plans. Future trends in the development of environmental flow recommendations in Central America and elsewhere should also take projected climate change into consideration, given that altered patterns of precipitation under future climate scenarios may decrease the water available for hydropower and for ecosystems.

⁷⁴ Chaves et al. n.d.

⁷⁵ Scatena 2004.

⁷⁶ Esselman and Opperman 2010.

8. Riverscape-Scale Planning and Regional Communication Networks

The environmental and social consequences of most hydropower projects in Central America are evaluated on an individual basis, and impact studies often are heavily focused at a local scale. However, with the concentration of multiple dams on single river basins (e.g., San Carlos and Sarapiquí in Costa Rica) or within key ecoregions or ichthyological provinces, there is a need to understand both the basin- or region-scale effects of individual hydropower projects as well as the cumulative effects of the construction and operation of multiple dams. This kind of thinking is necessary for protecting ecologically sensitive or representative areas as well as important populations or ecological processes, all of which can be linked to freshwater ecosystem services.

Central America has a history of regional collaboration on conservation efforts. The Mesoamerican Biological Corridor stands out as a strong example, but like many of the region's conservation initiatives, it has been heavily focused on terrestrial ecosystems. While regional conservation initiatives targeting freshwater ecosystems remain rare, some promising examples are emerging. In Costa Rica, a gap analysis for freshwater biodiversity conservation was undertaken between 2006 and 2007 to identify conservation goals.⁷⁷ In terms of rivers, this analysis identified 64 different kinds of lotic ecosystems within Costa Rica, but it also noted that only 47 of these were present in existing protected areas—and only 23 of those were actually achieving established conservation goals for freshwater. Further, of the 18 species of fish known to be endemic to Costa Rica, only 13 were found to have 10 percent or more of their distribution area covered by a protected area. Beyond these quantitative results, the analysis also indicated that protecting terrestrial areas in river basins would not necessarily sustain freshwater ecosystems or guarantee the survival of freshwater species.⁷⁸ Rather, freshwater ecosystem conservation depends on maintenance of hydrologic connectivity at a landscape scale, and protection of longitudinal (upstream-downstream), lateral (river-floodplain), vertical (surface water-groundwater), and temporal pathways along which water, organisms, and matter move.⁷⁹

In northeastern Central America, research on the distribution of freshwater fishes is being incorporated into recommendations for the design of reserve networks for freshwater ecosystems.⁸⁰ Rather than apply traditional concepts of terrestrial protected areas, the approach

⁷⁷ Paaby 2008.

⁷⁸ *Ibid.*

⁷⁹ Ward 1989; Pringle 2001.

⁸⁰ Esselman and Allan 2011.

used identifies three management units that better relate to freshwater complexity. These units are the freshwater focal area, or the specific location of a freshwater feature in need of protection; the critical management zone, which complements freshwater focal areas and helps maintain their functionality; and the catchment management zone, which considers the entire surrounding catchment of a freshwater focal area or critical management zone and where integrated resource management principles should be applied.⁸¹ Commonly available sources of data (e.g., FishBase, museum records, the Global Biodiversity Information Facility), species distribution models, and conservation planning software can be used to define these units for freshwater fishes. For watersheds draining Belize, this approach has helped identify the location of freshwater conservation priorities, which of these currently overlap with existing protected areas, and where there are critical gaps in protection of freshwater fishes.⁸²

How can lessons learned from these initiatives be applied to hydropower development at a regional scale? First, these initiatives can help identify entire basins—or if not at that scale, river segments—that should be conserved on the basis of their ecological or social significance and current intact state (see the following recommendations as well). Second, the Tegucigalpa Protocol, the establishment of the Central American Integration System, and development of a regional electricity grid offer examples of ways that Central American countries recently have moved toward regional collaboration as related to hydropower. Although focused primarily on economic and grid integration, these networks could offer an opportunity for regional promotion of more ecologically and socially sustainable practices and protection of freshwater biodiversity and ecosystem services as well.⁸³ In fact, a new research and advisory program spearheaded by the Worldwatch Institute aims to support a process for improving social, environmental, and economic sustainability of energy systems on a regional scale. Among other activities, this program will establish a network to connect experts and stakeholders across the region, engaging them in a series of regional workshops for presenting best practices and sharing experiences as related to renewable energy in Central America.⁸⁴ The challenge will be to connect these networks to the community of professionals working toward improved scientific understanding and protection of freshwater ecosystems in Central America and to streamline the findings and approaches into energy-related discussions.

⁸¹ Abell et al. 2007; Esselman and Allan 2011.

⁸² Esselman and Allan 2011.

⁸³ Worldwatch Institute 2012.

⁸⁴ *Ibid.*

9. Exploration of Linkages between Hydropower and Other Conservation Initiatives in Central America

Beyond hydropower development, the Central American region currently is experiencing transformations of the landscape as related to changes in land use, growing human populations, and climate change. Strong interest in the conservation of natural, intact systems exists, and there may be opportunity for hydropower development to act as a catalyst or support for these conservation efforts.

Hydropower dams benefit from the maintenance of other ecosystem services (e.g., reduction in soil erosion and sedimentation, sufficient water quantity) associated with intact forests, particularly in areas upstream from dams. Efforts in Costa Rica and Nicaragua to map areas where hydropower benefits from these upstream ecosystem services indicate that these areas often overlap with already established priority areas for forest conservation. These efforts also identified one river basin in each country as a top priority for both forest conservation and restoration. In Costa Rica this is the Reventazón River Basin and in Nicaragua, the Matagalpa River Basin.⁸⁵ Costa Rica is renowned for its national Payment for Environmental Services (PES) program, which is a cornerstone of the country's forest conservation strategies. What is not as well known, however, is the important role that hydropower plants play in this program. Of the private sector, private hydropower plants are the largest contributors to the PES program and as of 2009 had accounted for 41 percent of all financing from private resource users, or \$919,000.⁸⁶ In fact, since the new water use "canon" for hydropower was approved in 2005, half of the funds paid must be reinvested in the watersheds, both in protected areas and private land (as per the Decreto Ejecutivo 32868-MINAE, published in La Gaceta No. 21 on January 30, 2006; M. Rojas, personal communication).

There is already some experience from the region of hydropower dam projects experimenting with conservation programs that involve a kind of offset program to compensate for rivers that are being altered by dams. In this case, intact river systems would be the target objects for conservation. Again, Costa Rica provides an example. The Reventazón Hydropower Project, currently under construction on the country's Caribbean slope, includes in its plan for environmental and social management a strategy for implementation of a protected river corridor

⁸⁵ Locatelli et al. 2011.

⁸⁶ Blackman and Woodward 2010.

with no barriers to connectivity in a river system that is ecologically similar to that of the Reventazón. The underlying idea behind this offset strategy is to aim for no net loss or net gain for biodiversity as a result of the construction and operation of the Reventazón Hydropower Project.⁸⁷ Although this strategy is commendable, consideration of questions of additionality (e.g., whether the offset river would be affected anyway in the future) should be a component in the evaluation of potential candidate systems for offsets.

10. Safeguard Some Rivers from Hydropower Development⁸⁸

Many Central American countries, most notably Costa Rica, made decisions in the twentieth century to set aside a substantial amount of national forests for conservation, investing in a system of protected areas that largely has been the backbone for a financially lucrative environment-based tourism industry. In Costa Rica, in particular, this tourism industry for years has been a main source of foreign currency in the country. Similar conservation choices could be made in Costa Rica and in other Central American countries to protect freshwater ecosystems, perhaps through designation systems similar to the U.S. concept of Wild and Scenic Rivers. Protection categories could be developed for river basins or individual rivers on the basis of ecological or socioeconomic importance and could allow for some uses while restricting others. The goal of these designations would be to ensure the persistence of free-flowing rivers in the Central American landscape, which based on current trajectories of hydropower development will become ever more scarce in the next 15 years.⁸⁹ Of all the recommendations made here, this last one is potentially the most important for maintaining some semblance of the region's unique freshwater ecosystems and their biodiversity in the current century and beyond.

11. Conclusions

Central America appears to be at a crossroads. The region has experienced extensive hydropower development over the past three decades, accompanied by a set of lessons about the ecological and social consequences of dams. At the same time, positive examples are emerging from across the region of how hydropower can be incorporated into more landscape-scale planning or how conservation initiatives can better protect freshwater ecosystem services. Hydropower is likely to

⁸⁷ IDB 2012.

⁸⁸ Anderson et al. 2006b.

⁸⁹ CEAC 2012.

be a cornerstone of Central America's energy future, and therefore a strong need exists to learn from the challenges of the past and to share innovations for conservation and management as related to freshwater resources at a regional scale.

Tables

Table 1. Freshwater Ecoregions of Mesoamerica and Their General Characteristics

Name	Country or Countries	Approx. Area (km²)	Approx. Length of River Ecosystems (km)
Tehuantepec-Golfo de Fonseca	Mexico, Guatemala, Honduras, El Salvador	92,256	92,031
Quintana Roo-Motagua	Mexico, Belize, Guatemala, Honduras	27,039	24,242
Honduras Caribbean	Honduras, Nicaragua	121,748	117,108
Estero Real - Tempisque	Honduras, Nicaragua, Costa Rica	28,295	27,514
San Juan	Nicaragua, Costa Rica	105,325	93,577
Térraba - Coto	Costa Rica, Panama	12,954	11,804
Isthmus Caribbean	Costa Rica, Panama	10,672	8,684
Chiriqui	Panama	12,419	6,737
Azuero	Panama	15,702	13,648
Chagres	Panama	11,953	8,796
Tuira	Panama	23,655	21,205

Source: TNC 2009

Table 2. Trends in Central American Electricity Sector, with Relative Contribution of Hydropower to Installed Generation Capacity and to Net Electricity Generated, 1990–2011, in Six Countries*

Year	Installed Capacity (MW)			Net Generation (GWh)		
	Total	Hydro	Percent Hydro	Total	Hydro	Percent Hydro
1990	4 129.3	2 708.6	66	14 175.2	12 165.9	86
1995	5 218.4	2 797.0	54	19 454.4	11 468.5	59
2000	7 258.3	3 314.7	46	26 955.4	15 417.8	57
2005	9 134.0	3 881.0	42	34 504.0	17 050.3	49
2010	11 205.4	4 490.7	40	40 668.2	20 974.4	52
2011	11 864.6	4959.3	42	42 115.2	20 623.9	49

Source: UN-CEPAL 2012

* El Salvador, Guatemala, Honduras, Nicaragua, Costa Rica, Panama.

Table 3. Comparisons of Electricity Sector and Relative Contributions of Hydropower in Central America and Six Countries
Source: UN-CEPAL 2012

	Installed Capacity (MW)			Net Generation (GWh)		
	Total	Hydro	Percent Hydro	Total	Hydro	Percent Hydro
Central America	11864.4	4959.3	42	42115.2	20623.9	49
Costa Rica	2650.2	1643.7	62	9759.6	7134.6	73
El Salvador	1503.5	486.5	32	5812.7	2075.4	36
Guatemala	2590.5	902.3	35	8146.6	4094.2	50
Honduras	1731	528	31	7126.5	2809.6	39
Nicaragua	1093.7	105.3	10	3567.3	438.2	12
Panama	2295.7	1293.5	56	7702.5	4071.9	53

* El Salvador, Guatemala, Honduras, Nicaragua, Costa Rica, Panama.

Table 4. Examples of Criteria for Considering Environmental, Social, and Economic Impacts of Hydropower Projects. Most of these should be considered in the early stages or preparation phases of a project, following assessments of demonstrated need for water and energy services and of all available options to meet those needs. The assessments should identify a proposed dam as a priority option for meeting demonstrated needs for water and energy services.

Impact	Measures for Considering Impact and Associated Environmental, Social, and Economic Trade-offs	Examples of Related Impact Avoidance and Mitigation Options
Flooding of natural habitats and loss of terrestrial wildlife	<ul style="list-style-type: none"> ▪ Flooded ha / MW ▪ Species / ha ▪ Endemic species / ha ▪ Potential greenhouse gas emissions / ha (CO₂, CH₄) 	<ul style="list-style-type: none"> ▪ Select dams sites that minimize flooding, particularly in ecologically sensitive areas or areas with high species richness and endemism and in forested areas ▪ Aim for low ha/MW ratio; low species / ha ratio; low endemic species / ha ▪ Designation of compensatory, ecologically similar protected natural areas or strengthening of protection and management of existing areas with weak support
Involuntary displacement of people	<ul style="list-style-type: none"> ▪ Ratio of persons displaced / MW ▪ Ratio of persons of vulnerable group (e.g., indigenous, women, minorities) / MW 	<ul style="list-style-type: none"> ▪ Avoidance of culturally important sites, densely populated areas, and areas inhabited by ethnic minorities or other vulnerable groups ▪ Aim for low person displaced/MW and low person of vulnerable group displaced/MW ratios ▪ Resettlement of displaced populations in similar or improved conditions ▪ Consultation and participatory decision making by resettled and host populations
Loss of livelihoods (e.g., based on fisheries, agricultural or grazing lands, building materials, or other resources)	<ul style="list-style-type: none"> ▪ Percentage of local population whose livelihoods are to be affected ▪ Percentage of local economy linked to affected resources ▪ Potential for replacement or alternative livelihoods 	<ul style="list-style-type: none"> ▪ Avoidance of sites where local livelihoods are largely linked to environmental resources ▪ Income restoration assistance, provision of replacement resources, or new job training for affected people
Downriver hydrological changes and connectivity losses	<ul style="list-style-type: none"> ▪ Ratio of length (meters) of dewatered section / MW ▪ Presence of migratory aquatic species ▪ Percentage of aquatic fauna that are migratory 	<ul style="list-style-type: none"> ▪ Shorter length of dewatered section is preferable, or low meters dewatered/MW ratio ▪ Management of prescribed water releases that mimic natural flow regime and account for important flow-ecology linkages or flow-ecosystem services linkages (environmental flows) ▪ Avoidance of rivers with high percentage of migratory species ▪ Consideration of options for maintaining some connectivity between upstream and downstream reaches (e.g., dams blocking only a part of

		<p>the channel, effective passage facilities)</p> <ul style="list-style-type: none"> Implementation of river “offsets”—protection and maintenance of natural conditions in comparable rivers without dams or other barriers to connectivity Sponsorship of scientific research into flow-ecology relationships and flow-ecosystem services relationships
Project location in a river network	<ul style="list-style-type: none"> Percentage of river basin upstream from dam sites (cumulative) Presence of ecologically sensitive areas upstream from dams and percent of area (cumulative) Percentage of headwater areas or km of headwater network upstream from dams (cumulative) 	<ul style="list-style-type: none"> For basins with no dams, minimize percentage of river basin upstream from dam sites, and percentage of headwater areas upstream from dam sites For basins with existing dams, consider cumulative percentages of river basin area upstream from dam sites and headwater areas upstream from dam sites, and minimize additional losses in connectivity with these upstream areas as result of new project Consideration of options for maintaining hydrologic connectivity between headwaters and downstream areas, for export of sediment, nutrients, and organic matter from headwaters
Reservoir sedimentation and deterioration of water quality	<ul style="list-style-type: none"> Natural sediment load of river Nonforested land uses in watershed upstream from dam site (e.g., percentage of agricultural, urban, pasture land uses) Kilometers of connected riparian forest (longitudinally / along river channel) and average width of riparian corridors upstream from dam Presence of diseases with water-dependent disease vectors in the region (e.g., malaria, schistosomiasis) 	<ul style="list-style-type: none"> Watershed management and control of land use upstream from dam, especially maintenance of intact forest or reforestation of cleared areas Incentives for maintenance of riparian corridors or support for enforcement of existing legislation as related to width of riparian zones Water pollution control measures (e.g., sewage treatment, industrial regulations) Control of floating aquatic vegetation in reservoir Preventative public health measures for minimizing disease exposure (e.g., awareness campaigns, bednets, monitoring of vectors and disease outbreaks)
Impacts of complementary civil works (e.g., access roads, transmission lines)	<ul style="list-style-type: none"> Kilometers of new roads to be constructed Kilometers of transmission lines from dam site 	<ul style="list-style-type: none"> Minimize kilometers of new access roads and transmission lines needed for project Avoid construction of new access roads and transmission lines through intact forest; where this is unavoidable, implement complementary forest conservation measures or establish protected areas Implement accepted best practices for siting, engineering, and construction of new roads and transmission lines

Sources: World Commission on Dams 2000; Ledec and Quintero 2003; UNEP Dams and Development Project 2007; International Hydropower Association 2010. MW= megawatts of installed capacity; ha= hectare

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