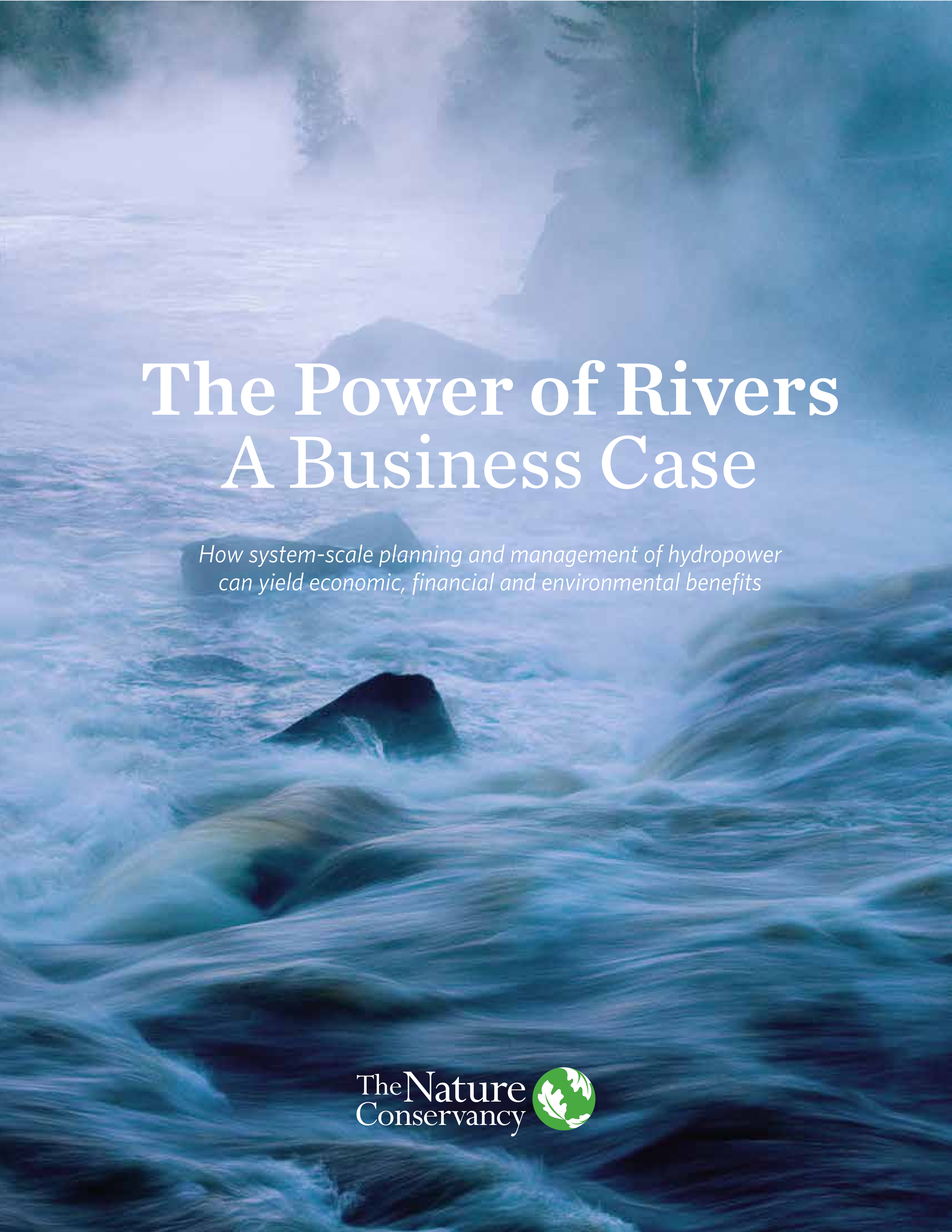

The Power of Rivers
A Business Case

How system-scale planning and management of hydropower can yield economic, financial and environmental benefits

The Nature Conservancy

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Reviewers
The following people served as reviewers and helped strengthen the report. The content and positions expressed in this report, however, are those of the authors and do not necessarily reflect the perspectives of those who provided input.

Emmanuelle Boulet (Inter-American Development Bank), Judith Plummer Braeckman (University of Cambridge), Emmanuelle Branche (EDF), Jean-Michel Devernay, William Girling (IHA), Marc Goichot (WWF), Stuart Heather-Clark (ERM), Cameron Ironside (IHA), Daniel Kammen (University of California, Berkeley), Upmanu Lall (Columbia University), Jian-hua Meng (WWF), Vijay Modi (Columbia University), William Rex (The World Bank), Mathis Rogner (IHA), and Maria Ubierna (IHA)

This report would not have been possible without the financial support of the following institutions or individuals:
Bank of America Charitable Foundation, The Caterpillar Foundation, Department for International Development (DFID), Goldman Sachs Center for Environmental Markets, Prince Albert Foundation, and Mary Anne (MA) and Jim Rogers

Please cite as:
Opperman, J., J. Hartmann, J. Raepple, H. Angarita, P. Beames. E. Chapin, R. Geressu, G. Grill, J. Harou, A. Hurford, D. Kammen, R. Kelman, E. Martin, T. Martins, R. Peters, C. Rogéliz, and R. Shirley. 2017. The Power of Rivers: A Business Case. The Nature Conservancy: Washington, D.C.

This report was developed in partnership with McGill University, The University of Manchester and PSR.

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Prologue

Giulio Boccaletti, PhD
Chief Strategy Officer and
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The Nature Conservancy

As our global population exceeds 9 billion people, the world will continue to look to rivers. We will look to rivers to support the rising needs of agriculture and industry. We'll rely on them for more drinking water, and we'll harness them to meet our energy needs.

Rising demand for energy, along with global targets for low-carbon electricity, is driving major expansion in renewables. Hydropower currently offers nearly twice the energy generation of all other renewables combined, and its contributions will grow as the world commits an estimated nearly US$2 trillion of investment between now and 2040.

But on this path to economic growth and keeping the climate within safe boundaries, we are faced with complex tradeoffs. The International Union for the Conservation of Nature (IUCN), for instance, has rated dams for hydropower and other uses as a leading challenge to freshwater biodiversity due to impacts on river flows and fragmentation—threatening freshwater fisheries that provide food security to hundreds of millions of people.

So what is the answer? How do we reconcile the world's needs for what free-flowing rivers provide and what developed rivers provide?

In our 2015 report, The Power of Rivers, we illustrated how a system-scale solution we call Hydropower by Design (HbD) could help keep tens of thousands of river kilometers free-flowing compared to what would occur through a business-as-usual approach—all while allowing energy generation to meet global targets.

Of course, we recognize that to realistically deliver on that potential, we must also illustrate the value of HbD beyond environmental gains. In this latest report, The Power of Rivers: A Business Case, we examine a range of economic, social and financial benefits available to nations who move beyond a project-by-project approach and consider implications to the full river system.

HbD is guided by the integration of water-management, environmental, energy and financial models. These models not only identify ways to realize broader financial efficiencies, but also reduce the risk of conflicts, cost overruns and time delays due to environmental and social impacts—all of which could undermine hydropower's potential to contribute to a renewable energy future.

At The Nature Conservancy, we draw from more than 60 years of science-based conservation to help people and nature thrive together. By working with governments, industry and other stakeholders, we believe it's possible to identify realistic development pathways to advance the world's resource needs while also protecting our vital underlying natural systems. For hydropower, this means keeping thousands of kilometers of free-flowing rivers intact while providing clean energy sources to people around the world.

I think we can all agree that reducing climate risk, boosting economies and standards of living for billions of people, and maintaining and restoring the value of river systems are all critical for people and the planet. Considering any of these great challenges in isolation means we fall short somewhere. Our chance for a sustainable future will come only from collaborative, innovative and holistic thinking.

Executive Summary

Hydropower by Design can identify strategic and sustainable hydropower systems that deliver economic value to countries, financial value to developers, and greater environmental values from rivers.

KEY POINTS

- System-scale approaches to planning and managing hydropower—what we call Hydropower by Design (HbD)—can produce significant economic benefits for countries, while reducing environmental impacts, social conflict and investment risk.
- Through a series of case studies we demonstrate that Hydropower by Design can result in improved environmental performance for similar levels of energy generation, along with economic gains of 5 to more than 100 percent in other important river services.
- While the strategic planning required to achieve those balanced outcomes has often been equated with delayed implementation or associated with projects that are not financially attractive, we used in-depth financial and energy system modeling to show that the risk-management and engineering optimization benefits of Hydropower by Design can result in projects that are: one, financially competitive; and, two, strategic and low impact.
- In effect, the strategic economic and environmental benefits of system planning can be "paid for" by the financial benefits of Hydropower by Design. The potential global economic benefits of widespread adoption of Hydropower by Design are large: even a 5 percent improvement in other water-management resources in river basins where hydropower plays, or will play, a major role would produce up to US$38 billion per year in benefits, a sum comparable to average annual investment in hydropower.

Hydropower will be an important contributor to low-carbon energy systems, representing nearly US$2 trillion of investment between now and 2040. In river basins across the world, hydropower development and management will have potential positive and negative impacts on other uses of water resources valued at between US$285 and US$770 billion per year.

- To maintain the climate within safe boundaries, the world must rapidly decarbonize its energy systems, including a tripling of generation from low-carbon sources of electricity. Alongside the dramatic expansion of solar and wind, hydropower will likely remain a key technology, both to balance grids and to add capacity (Figure 1).
- Forecasts that assume the world meets its climate commitments suggest global hydropower capacity will increase by at least 50 percent by 2050, from 1,200 GW to approximately 2,000 GW (Figure 2). Based on average investment costs, this represents a total investment pool of US$2 trillion. Asia will see the largest total increase, while Africa will experience the largest proportional increase.
- Hydropower development and management occurs in river basins with other diverse demands for water resources. Hydropower that is planned and operated as part of a larger system (such as a river basin, power grid, or jurisdiction) has the potential to increase the benefits from these resources. However, hydropower that is not considered part of a system will tend to miss out on opportunities to benefit other demands and can, at times, even conflict with them. Within hydropower-influenced basins (HIB) the total economic value of water-management services is very large (Figure 2), estimated to be between US$285 and US$770 billion per year:

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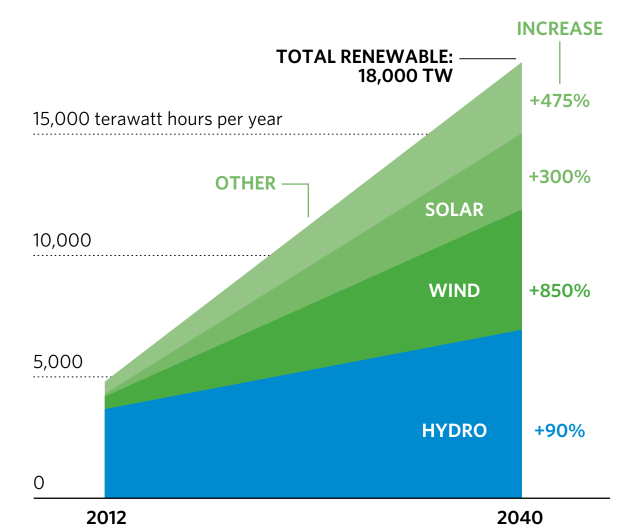
- 180 million hectares of irrigated land, providing between US$100 and US$410 billion in annual economic value.
- 660 million people and 145,000 square kilometers at risk of flooding within urban areas; annual flood damages within the HIB range from US$20 to US$40 billion and can be interpreted as the potential value of flood management.
- 88,000 million cubic meters (MCM) of reservoir storage for water supply, sufficient to support approximately 600 million people with drinking water, with an estimated economic value between US$160 and US$320 billion.

FIGURE 1

Projected increases in sources of low-carbon energy required to meet 2040 climate objectives, at which point renewables would represent over half of electricity generation.[1]

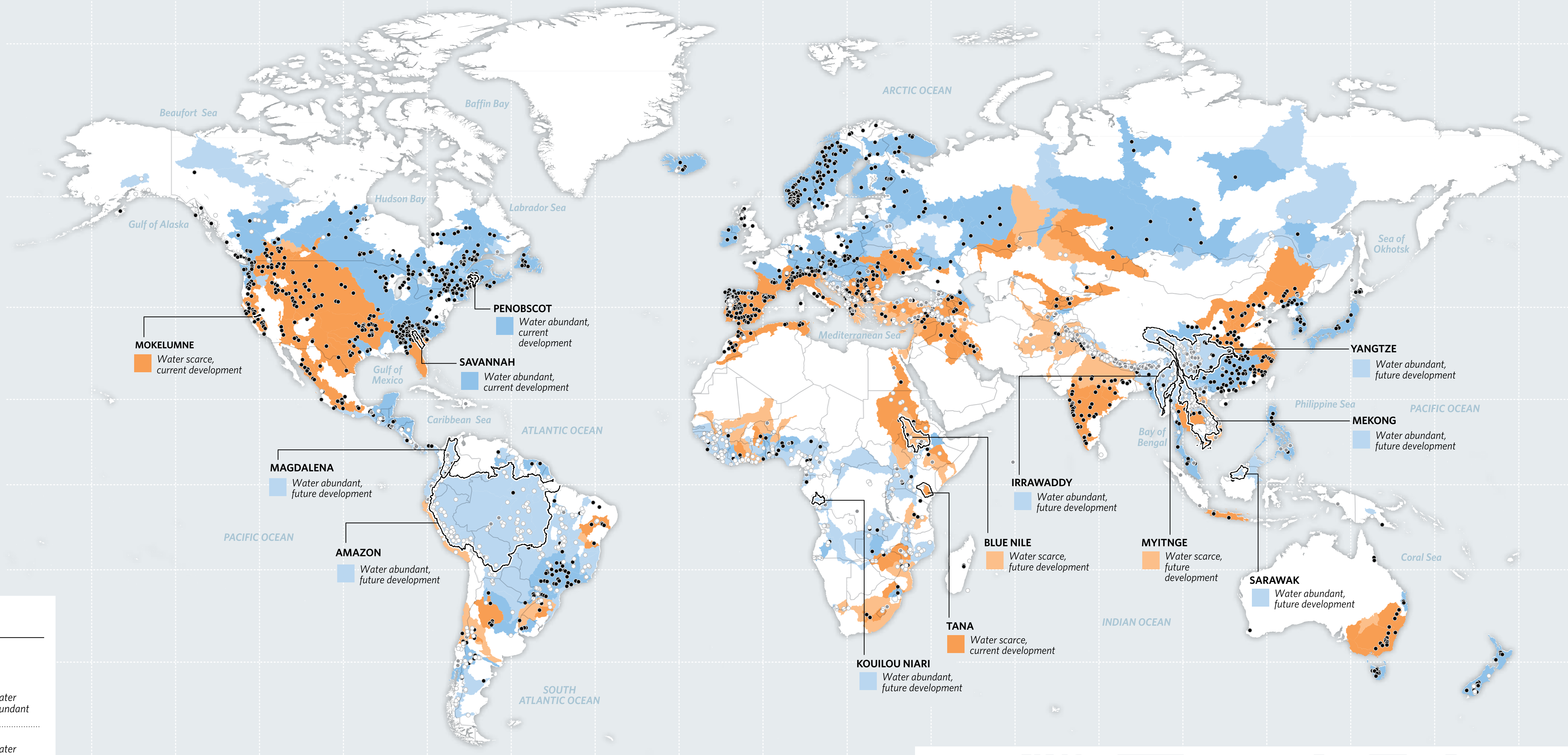


1 IEA, 2014

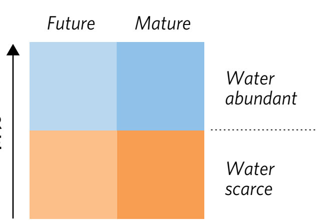
FIGURE 2

Hydropower influenced basins; blue shading indicates those with abundant water; dark blue are "mature" in terms of development ("current development") and light blue have most development in the future. Orange shading indicates area where water is more scarce; dark orange are "mature" ("current development") and light orange have development in the future. Solid dots are existing hydropower dams, gray dots are hydropower dams under construction and open circles are planned or potential hydropower dams. Case study basins are highlighted.

The bar charts in the lower left reflect levels of water supply storage, people at risk of flooding in urban areas, and hectares of land irrigated by surface water compared across the four types of hydropower influenced basins ("future" = "future development"; "current" = "current development"; "abundant" = "water abundant"; "scarce" = "water scarce").



CATEGORIES OF BASINS



BASIN TYPE	WATER SUPPLY STORAGE (MCM)	FLOOD RISK (MILLION OF PERSONS)	IRRIGATED LAND (HA)
FUTURE ABUNDANT	888	70	16
MATURE ABUNDANT	42,317	238	22
FUTURE SCARCE	6,531	97	53
MATURE SCARCE	38,157	256	88

- EXISTING HYDROPOWER DAM
- UNDER CONSTRUCTION
- PLANNED

© MICHAEL YAMASHITA (DALAH MARKET, MYANMAR)

However, this expansion of hydropower must be done right. If planned in isolation (e.g., at the project scale and/or without incorporating objectives for those other resources) hydropower projects will generally fail to achieve their full potential for providing multiple benefits. They could, in fact, cause significant negative impacts on more than 300,000 kilometers of rivers and their associated environmental and social values.

- Development based strictly on single-project financial criteria can result in hydropower projects that provide generation but do not contribute to broader energy goals—such as integrating intermittent renewables onto the grid—and, by occupying an advantageous site, can even make it harder to achieve those goals.

- Poorly planned hydropower, along with missed opportunities to achieve broader benefits, have contributed to social conflicts around hydropower development and operation. For existing projects, conflicts can lead to litigation and compulsory retrofits or changes to operation. For projects in the planning or construction stages, conflicts can contribute to delays, cost overruns and cancellations. Hydropower projects are often large, complicated projects that are very site specific and thus a wide range of factors can contribute to these problems. However, social and environmental conflicts can be major factors and the significant impacts of some hydropower no doubt contribute to the fact that hydropower projects have higher delays and overruns compared to other large infrastructure projects. These, in turn, contribute to perceptions of risk and uncertainty that can affect the flow of investment. High-profile recent examples of delayed, suspended or cancelled projects—including Myitsone (Myanmar), HidroAysen (Chile), Sao Luis do Tapajos (Brazil) and Belo Monte (Brazil)—provide compelling examples of how incomplete consideration of environmental and social impacts during planning and site selection can lead to significant challenges to developers and investors. The first three of these projects represent an aggregate of US$1.3 billion in stranded investment and 18 GW of undeveloped capacity.

- The environmental and social costs of this expansion of hydropower could be enormous. Negative impacts on ecosystems and people from hydropower are well-documented through both actual and modeled outcomes, such as a projected 40 to 60 percent decline in migratory fish biomass in the Mekong River basin from full development of mainstem dams. Within high-income countries, dams are already a leading cause of extinction of freshwater species and the decline of freshwater ecosystem services. The projected levels of development of new hydropower, largely in lower- and middle-income countries, could impact more than 300,000 kilometers of free-flowing rivers, with the majority of those impacts occurring in rivers that provide the greatest benefits to rural communities through food production and livelihoods. For example, river basins with the most projected expansion of hydropower currently support at least 6 million tons of fish harvest, enough to be the primary source of animal protein for 130 million people.

Governments confront an apparent dilemma: system-scale planning and management can reduce these negative environmental and social impacts and ensure that hydropower achieves its full potential contribution to a country's strategic objectives for energy and water, but governmnents often believe that system-scale planning is associated with implementation delays and projects that are less attractive financially.

- Strategic planning has often been equated with long and cumbersome processes and a government may be concerned that this approach will identify projects and management options that are in the country's strategic interest, but which are not financially attractive to developers and investors, inhibiting the flow of investment to meet development needs. From this viewpoint, selecting strategic development pathways would come at a cost of delaying or inhibiting investment.

- On the other hand, projects selected primarily due to financial attractiveness to developers may encourage investment, but result in projects with higher impacts and that contribute less effectively to broader strategic goals, such as economic value.

- What's needed are processes and tools that can identify development and management options that are: one, strategic and low impact; and, two, financially competitive.

2 Migratory fish represent the most important part of the current fishery, valued at US$11 billion per year and the primary source of protein and livelihood for tens of millions of people.
3 Note that freshwater fish harvests are generally under-reported, so the actual totals are likely considerably higher.

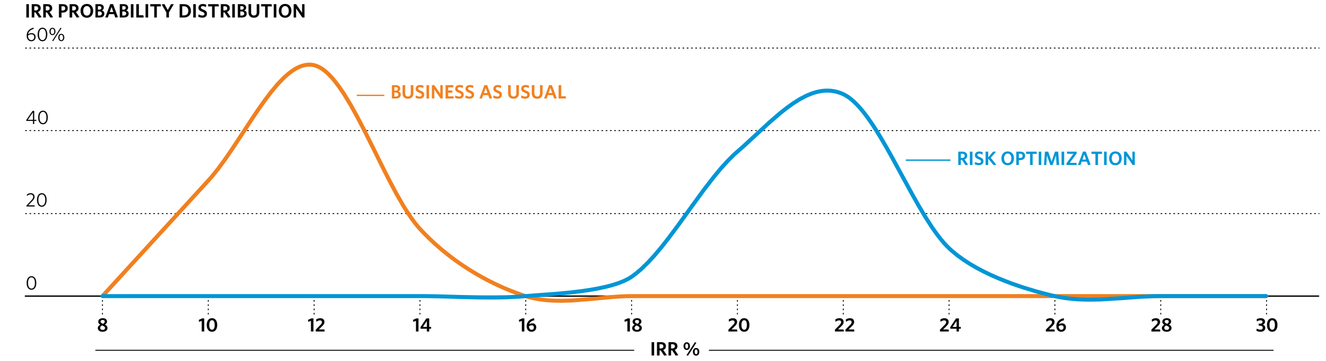
Hydropower by Design can be broadly defined as a comprehensive and system-scale approach to hydropower planning and management that fully integrates other sectors and environmental and social issues from the earliest stages to promote sustainability and optimize delivery of benefits.

Hydropower by Design's integration of perspectives and models makes it is possible to capture two key sources of financial value: one, system design optimization; and, two, improved risk management to reduce delays and cost overruns due to environmental and social impacts. Hydropower by Design (HbD) can identify portfolios of projects that have superior Internal Rate of Return (IRR) values. These superior returns can "pay for" economic, social or environmental objectives. Through the application of HbD—which generates a pipeline of strategically compatible projects that also have competitive IRRs—countries can afford to be strategic.

- Hydropower is often developed through a set of disconnected project-level decisions. The single-project approach misses opportunities to capitalize on system-scale financial value because each individual project, built to meet expectations of a single developer, changes the physical context in the basin (e.g., flows, transmission lines and other infrastructure) for all future development opportunities. The HbD approach to project selection—guided by the integration of water-management, environmental, energy and financial models—embeds decisions about individual projects within a system optimization, identifying a set of projects that capture system-level financial efficiencies. This results in a portfolio of individual projects with greater average financial performance than project-by-project, "business as usual" (BaU) approaches.
- A second source of financial value compared to BaU arises through improved identification and management of risks, which can inform site selection and design and contribute to reduced conflicts, cost overruns and time delays due to environmental and social impacts. Delays can cause significant reductions in projects' IRR, as each month a project is delayed is a month of additional expenditures and foregone revenues. By bringing water resource management and ecosystem models into the selection and design process for new projects, project risks can be assessed more realistically and risk projections can be incorporated into investment return models. This results in a portfolio of projects with lower risks, improving the distribution of projects' IRR compared to the BaU approach.
- By capturing these sources of financial benefit, projects selected under a Hydropower by Design approach in a case study from Colombia could meet energy objectives with 66 percent less social impact and 5 percent fewer environmental impacts when compared to a BAU approach, while at the same time achieving a greater average IRR (22 percent versus 13 percent; Figure 3) and a superior NPV ($5.3bn versus $2.4bn).

FIGURE 3

A comparison of the modeled distribution of Internal Rate of Return (IRR) for a set of individual projects selected through Hydropower by Design ("risk optimization") and through Business as Usual approaches for the Magdalena River in Colombia.



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Hydropower by Design (HbD) can identify options that provide similar levels of generation as business-as-usual (BaU) approaches, but do so with lower environmental impacts and achieve improvements from 5 percent to more than 100 percent for other water management values, such as irrigation and migratory fish habitat.

- Hydropower by Design offers the potential for broad economic benefits to countries. In a set of modeled case studies, HbD approaches to planning and management were able to increase the level of other economic values by 5 percent to more than 100 percent compared to BaU, generally with no or limited reduction in energy generation and, in some cases, an increase in generation. In basins where water is scarce and reservoirs tend to have multiple purposes, these other economic values included irrigation, water supply, flood management and floodplain livestock. Within basins where water is abundant, hydropower dams are often single purpose, though flood management and water supply were also improved in some of these basins. In nearly all of the basins, environmental performance could be improved (Figure 4). These improvements are highly basin-specific due to the complicated nature of interacting economic, social, infrastructure and biophysical systems.
- For many resources, larger improvements are possible when Hydropower by Design is implemented at the planning stage and can influence site selection.
- River basins are inherently complex with site-specific combinations of resources, constraints and opportunities. For example, while performance for some resources may be positively correlated in one basin, they may be negatively correlated in another. Thus, extrapolating from a set of case studies to a global perspective confronts substantial challenges. Nevertheless, it is instructive to consider the potential global scope of improved economic performance that could arise from widespread use of Hydropower by Design. For example, if system-scale approaches to hydropower planning and management could achieve a net improvement of even 5 percent in other water management services, then that would result in increased global economic value of approximately US$14 to US$38 billion per year, a number that is comparable to average annual investment in hydropower. This underscores that countries and development organizations should be motivated to promote the planning, decision-making, financing and regulatory processes necessary to secure these potential gains. The realization that greater than 5 percent improvement may be possible in many areas should further motivate implementation.

The Way Forward: Hydropower by Design can be implemented in ways that are practical, affordable and timely.

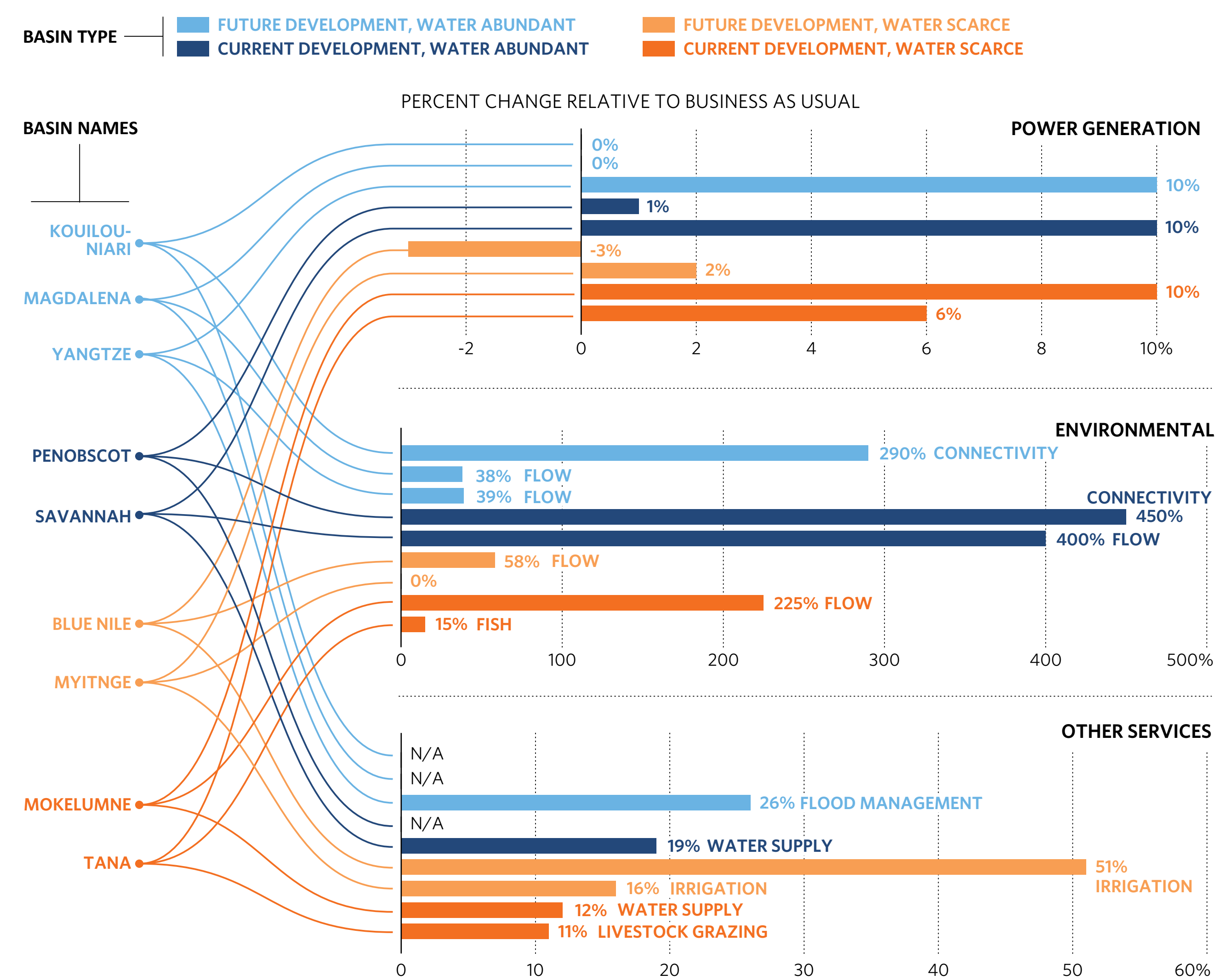
- Through new modeling tools and a process that bring together diverse objectives, data sources and families of models, Hydropower by Design can deliver useful insights about development and management options in a relatively short period of time. Rather than delaying decisions or investments, these system-level tools and approaches may reduce project-level uncertainty and delay, thereby reducing investment risk.
- Hydropower by Design is not an entirely new process, but rather its principles and tools can be integrated into existing planning and regulatory processes, ranging from generation options assessments to basin master plans or strategic environmental assessments.

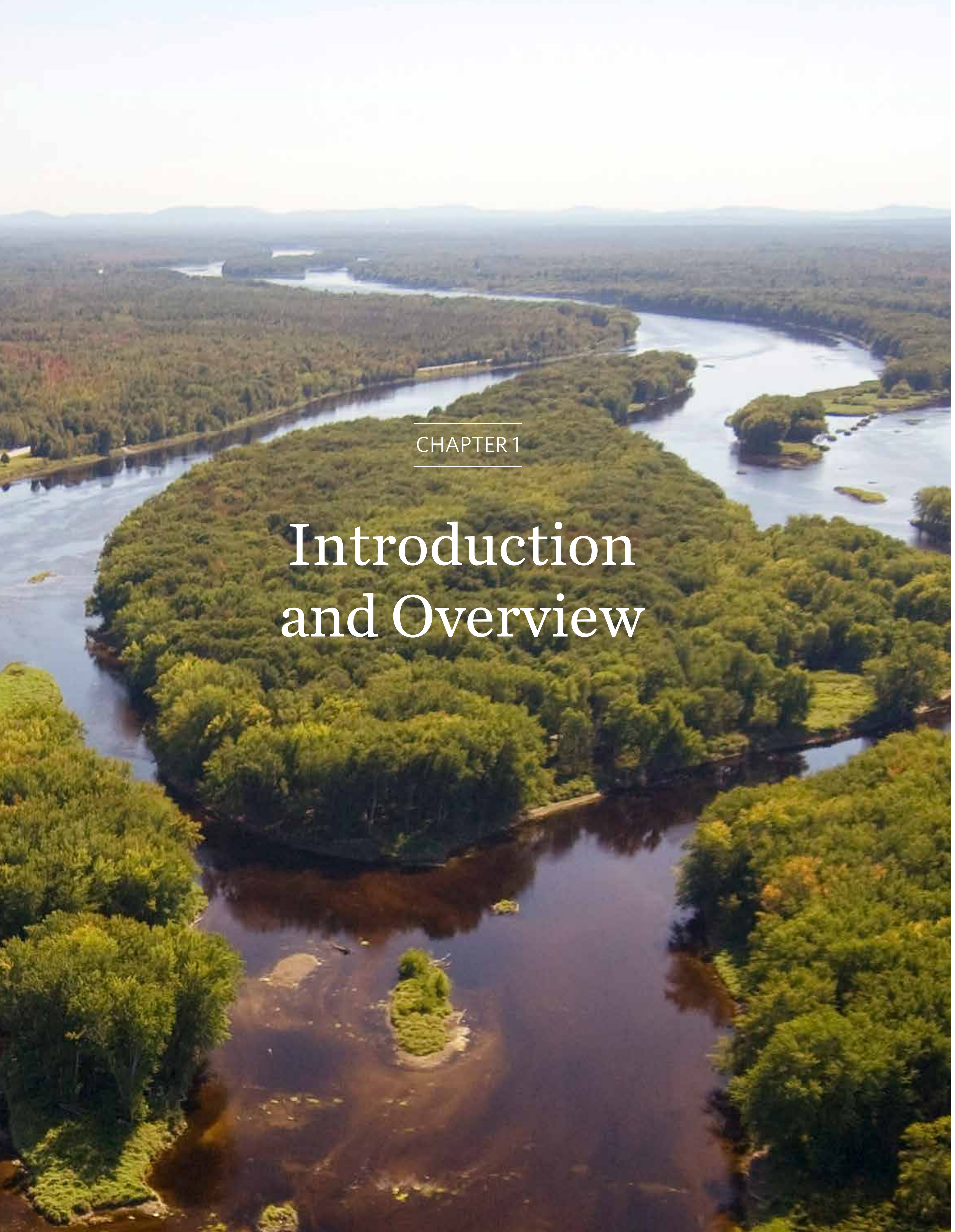
A number of mechanisms can be used to promote the system planning and balanced outcomes described in this report:

- A project preparation facility that: one, includes upstream planning capabilities to help governments select project sites based on system-scale HbD principles; and then, two, prepares the sites with midstream project preparation work. This type of facility could assist development banks' access to a high-quality pipeline of pre-selected, bankable projects that also meet the host country's broader strategic objectives.
- Based on a strategic planning process, governments can use auctions to identify developers for pre-selected strategic projects, making those projects more attractive by offering access to power purchase agreements, payments for firm energy, or guaranteed feed-in tariffs.
- Access to development bank loans, green bonds and other preferential sources of capital can be made easier for projects selected through a strategic planning process.
- Environmental agencies can incorporate the mitigation hierarchy into environmental review, licensing processes and mitigation requirements. Additionally, the permitting process for pre-selected projects can be fast-tracked, as there will be more comprehensive information available on the project and system objectives at an early stage.

FIGURE 4

Economic and environmental improvement possible through application of Hydropower by Design in case studies from nine river basins. In each case, a Hydropower by Design (HbD) scenario was compared to a Business as Usual (BaU) scenario with comparable financial cost and/or comparable economic cost. Basins were categorized based on their development status (current or future) and water availability (abundant or scarce).





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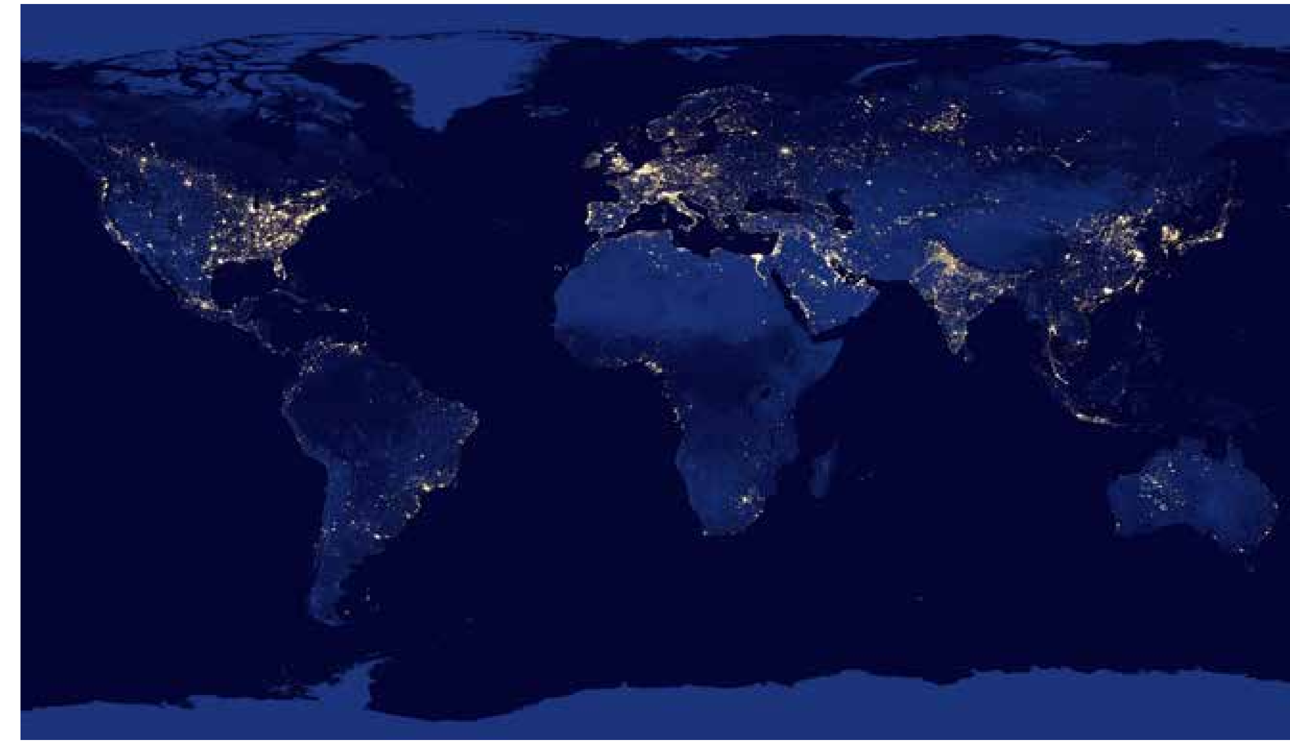
CHAPTER 1

Introduction and Overview



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Global challenges for climate, energy and rivers

Hydropower is a low-carbon source of energy that is expanding rapidly to meet growing global demands for electricity. Experts project global hydropower capacity will increase by at least 50 percent by 2050, particularly within future scenarios that assume the world takes the necessary steps to meet climate objectives.[1] Hydropower will play a key role in the transition to a decarbonized energy system, but hydropower dams can cause significant negative social and environmental impacts. Further, although hydropower investments can contribute to broader economic development goals, projects planned in isolation often fail to achieve that potential. These missed opportunities and environmental and social impacts contribute to conflict and uncertainty, which increase risk for investors and developers, reduce political support for hydropower and constrain hydropower investment and operations, including in ways that could undermine hydropower's potential to contribute to a renewable energy future.

Thus, hydropower development and management face a number of social, environmental, economic and financial risks. The world urgently needs solutions that lower these risks and produce broader benefits. Infrastructure decisions and policies made today will shape countries' economies and strongly influence whether the world succeeds in maintaining a stable climate. These decisions will also determine what kind of world we will live in after meeting those development and climate goals. The world's rivers and the diverse values they provide to people depend on sustainable solutions for energy and infrastructure.

(Photo Above) Global demand for electricity is projected to more than double between today and 2050.

1 IEA (2014) suggests capacity will increase by about 50 percent from current level by 2050; World Energy Council and PSI (2013) consider two possible scenarios, one that is fairly similar to the IEA and one that would be closer to 100 percent increase from current capacity.

REPORT STRUCTURE

Chapter 2 examines the role of hydropower as a provider of energy and energy services and its projected global growth, driven in part by climate objectives. To understand other drivers of dam development and management, this chapter also quantifies global levels of other water-management services within basins where hydropower is, or will be, important.

Chapter 3 describes the full range of other social, economic and environmental values that occur within hydropower influenced basins—and how hydropower development and management can negatively impact those values, leading to social conflict, uncertainty and risk for investors and developers.

Chapter 4 introduces HbD and summarizes how it can produce economic value for countries and financial value for developers and investors.

Chapter 5 is composed of nine quantitative case studies encompassing 13 river basins that demonstrate those economic and financial values of Hydropower by Design.

Chapter 6 describes how Hydropower by Design can be implemented through a range of existing mechanisms and explores some new mechanisms to promote its uptake.

Chapter 7 provides a summary and conclusions.

Appendix A provides greater detail on the framework of Hydropower by Design (principles, features, tools).

Appendix B summarizes a comprehensive implementation of HbD within Colombia's Magdalena River basin.

Appendix C provides greater depth on environmental and social impacts from hydropower.

Appendix D discusses how Hydropower by Design can increase resilience to climate change.

Appendix E provides the full methods behind the case studies and global roll-up of economic values.

Hydropower by Design

A range of studies and real-world examples demonstrate that those sustainable solutions will likely require the emergence and replication of system-scale approaches to the planning and management of hydropower and other energy and water-management infrastructure. In this report, we use the term Hydropower by Design to describe a framework of best practices for sustainable hydropower. Hydropower by Design (HbD) can be broadly defined as a comprehensive and system-scale approach to hydropower planning and management that fully integrates other economic priorities and environmental and social issues from the earliest stages to promote sustainability and optimize delivery of benefits.

In using the term, "Hydropower by Design," we are not implying that the hydropower sector fails to consider design. In fact, rigorous design guides hydropower development at multiple levels and has notably improved the sustainability of individual dams. However, a number of major impacts from hydropower cannot be mitigated effectively at the scale of a single dam. Further, project-level sustainability cannot address the complex issues posed by multiple hydropower developments across a river basin or region. These issues extend beyond managing environmental and social impacts. The limitations of project-level approaches also include missed opportunities to optimize how infrastructure systems provide water-management and energy benefits to people. Through HbD, we propose principles that integrate best practices at both the project and system scales to promote sustainability and deliver broader development benefits.[2]

In the 2015 report, The Power of Rivers, we showed that widespread adoption of Hydropower by Design could allow the world to meet 2040 hydropower generation targets with far lower impacts on rivers than would occur through Business as Usual (BaU) planning and management.[3] Our modeling results suggested that, if river basins across the globe were developed using HbD approaches, approximately 100,000 kilometers of rivers would remain free-flowing compared to what would occur through BaU approaches. Though that result is promising, achieving that potential will require broad uptake within the hydropower sector. Hydropower is developed and managed in an impressively complex context, driven by a set of economic, financial and political drivers. Catalyzing broad uptake will require that diverse decision makers see value in HbD beyond environmental gains.

2 Note that much of what we discuss and recommend in this report could pertain to all dams, not just hydropower dams. We focus on hydropower for several reasons. First, hydropower is a primary driver of new dam construction in many important river basins, such as the Mekong and Amazon. The World Commission on Dams (2000; Table 1.2) estimated that 60 percent of global investment in dams in the 1990s was for hydropower. Second, nearly all large, multipurpose dams include hydropower.

3 Opperman et al. 2015a

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ENERGY SYSTEMS BY DESIGN

Although this report focuses on Hydropower by Design, we would like to emphasize upfront that hydropower planning and management should be embedded within a broader planning and management framework for meeting energy and climate objectives. Hydropower by Design should be nested within an integrated planning approach for determining the right mix of generation sources to meet energy and climate goals, with a comprehensive assessment of the costs and benefits of different energy sources (economic, social and environmental) and how sources work together to meet the needs of an economy and society. This integrated approach can identify pathways that work for energy systems, ecosystems and communities (see case study on Sarawak in Chapter 5). From this integrated process will emerge specific targets for hydropower, in terms of capacity and generation, as well as functions within the system, such as load following. Hydropower by Design can then be used to find the best ways to meet those targets and roles.

The Business Case for HbD

In this report, we explore those values and develop a "business case" for Hydropower by Design and sustainable hydropower practices more broadly. Through a series of case studies we illustrate how HbD can offer a range of economic benefits to countries, increasing the ability for infrastructure investments to deliver development and environmental gains. Achieving those benefits depends on investment actually flowing. To ensure this occurs, infrastructure options identified through HbD must be financially competitive, which is why this report also explores the financial benefits to developers and investors.

This report is not about whether hydropower dams should be built. Deciding whether and how much hydropower to build and what type is a critical question facing many countries today, one based on a broad range of considerations that vary by geography and time. We do not try to recommend a specific level of hydropower development—in a country or in the world—but, instead, focus on the potential for more sustainable outcomes across a range of development and management pathways. The world faces a number of intertwined challenges: avoiding systemic harms from climate change; providing sufficient energy to support economies and allow billions of people to increase their standard of living; and, to maintain and restore the diverse cultural, economic and environmental resources from rivers. The system-planning approaches we describe here will give the world a better chance to achieve success across those challenges.

Further, by exploring a "business case" we are not suggesting that all protection or restoration of social or environmental resources must be justified on the basis of financial or traditional economic analyses. Although this report frequently compares alternatives where energy or cost are key decision variables, there remains a need for projects focused on conserving or restoring ecosystems and their social and cultural values, even if their positive economic benefit cannot be quantitatively demonstrated. For example, the protection of a culturally important river does not need to be justified by traditional cost-benefit analysis. However, this report is focused on demonstrating that, in many cases, this environmental improvement can occur through projects and programs that will appeal to those focused on the financial and economic bottom line, thus expanding the total implementation of environmental conservation and restoration. We believe that demonstrating this business case—and spurring greater uptake and experimentation with the types of solutions we describe here—can make an important contribution to achieving a world with a stable climate, prosperous societies and healthy rivers.

CHAPTER 2

The global expansion of hydropower and its role in energy and water-management systems

In this chapter, we review hydropower as a source of renewable energy services. We also describe the other water-management purposes that hydropower dams can provide or influence. Collectively, these energy and water-management benefits are the drivers of hydropower dam construction and the context within which dams operate. In the second part of the chapter, we estimate the global value of water-management benefits within river basins in which hydropower exerts—or will exert—a major influence on how rivers and water are managed.

Hydropower as a source of energy services

Hydropower (hydroelectric power) provides approximately 16 percent of electricity worldwide, although in some countries the proportion is much higher, including countries with high GDP (hydropower accounts for 98 percent of Norway's electricity) and with low GDP (Laos with 97 percent of its electricity from hydropower).[4] Nearly all forms of hydropower require the construction of a dam across a river (see Box 2.1). More than 58,000 "large dams" have been built globally and less than 25 percent of these have hydropower as a purpose.[5] The full number of dams, including small dams, exceeds a million.[6]

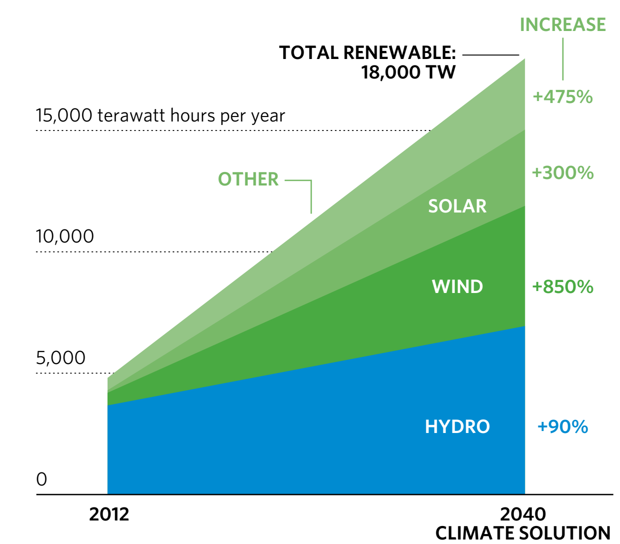
Rising demand for energy in emerging economies, along with the specific demand for low-carbon electricity globally, is driving a major expansion in hydropower, with more than US$50 billion in annual investments and approximately 65 GW of capacity added globally in the past two years.[7] To maintain the climate within safe boundaries, the world must rapidly decarbonize its energy systems, including a tripling of generation from low-carbon sources of electricity.[8] Hydropower is currently the largest source of low-carbon generation.[9] As of 2012, renewable sources of electricity generation produced 4,800 terawatt hours (TWh), representing 21 percent of total global annual electricity generation. Of that renewable total, hydropower provided just over 75 percent (3,670 TWh) and approximately six times more than wind and solar combined (Figure 2.1).[10]

CHAPTER 2 KEY POINTS

- Driven in part by policies to reduce emissions of greenhouse gases, global hydropower capacity is projected to increase from approximately 1,200 GW to 1,850 GW by 2050.
- Within river basins, hydropower planning and operations interact with a range of other water-management services, including storage for water supply, irrigation or flood management. These other services influence the demand for new infrastructure and hydropower management can have positive or negative impacts on these services.
- Within river basins that are, or will be, influenced by hydropower, the total economic value of other water-management services is very large, estimated to be between US$285 and US$770 billion per year.

FIGURE 2.1

The projected growth of various sources of low-carbon and renewable electricity to meet climate goals. In this projection, total renewable generation would reach just over half of global generation by 2040.[11]



4 Hamududu and Killingtveit, 2012
5 International Commission on Large Dams which defines a "large dam" as "A dam with a height of 15 metres or greater from lowest foundation to crest or a dam between 5 metres and 15 metres impounding more than 3 million cubic metres."; Branche, 2015.
6 Owens and Apse, 2015
7 IHA, 2017; 33.7 GW in 2015 and 31.5 GW in 2016
8 IEA, 2014
9 The IPCC estimates that life-cycle emissions from hydropower are five percent that of natural gas and three percent that of coal (Schlömer, et al., 2014), though note that certain types of reservoirs, particularly in the tropics, can have significant emissions and reservoir emissions are a topic of ongoing research (Deemer, et al., 2016).
10 IEA, 2014.
11 IEA, 2014

In addition to providing electricity, hydropower also provides a set of ancillary energy services that benefit an electrical system.[12] By storing water upstream of turbines—both in traditional reservoirs on rivers and in pumped storage reservoirs (Box 2.1)—hydropower reservoirs store water as potential energy that can quickly be converted to electrical energy and thus can contribute to load following and peaking, and thus grid stability. Storage in hydropower reservoirs provides the primary means of storing electricity (nearly 100 percent) on the planet and plays an important role in "firming up" variable sources of energy such as wind and solar.[13] Through this role, hydropower can facilitate greater penetration of variable renewables into an energy system.[14] Denmark's high proportion of wind-generated electricity (42 percent in 2015, with a stated goal of 84 percent by 2035) is made possible in part because of grid interconnections with Norway and the ability of hydropower to quickly provide Denmark with electricity during periods of low wind. Conversely, during periods of high wind, Norway can "store" wind power by buying electricity from Denmark and reducing flow from its hydropower reservoirs, thus increasing the potential energy stored in its reservoirs.[15]

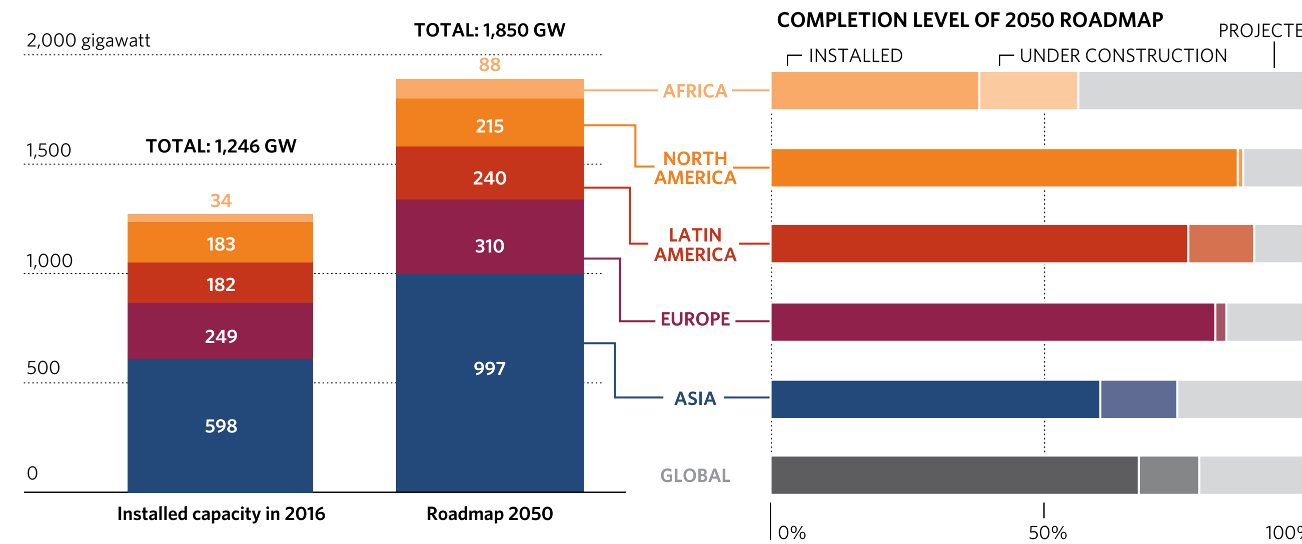
Hydropower thus has two important contributions in mitigating climate change: providing a direct source of low-carbon energy; and facilitating a larger proportion of renewables in an energy grid than would otherwise have been possible. Forecasts that assume the world meets its climate commitments generally project a continuing important role for hydropower. For example, IEA's energy scenario for achieving the objective of limiting global temperature increase to less than 2° C envisions renewable energy generation reaching 17,970 TWh (51 percent of global generation) by 2040 with much of that increase coming from a tenfold increase in wind and a thirtyfold increase in solar. Even though this projection forecasts a much lower relative increase for hydropower, it still has hydropower as the largest single source of renewable energy, providing 40 percent of the total renewable energy generation—nearly a doubling of 2012 generation to 6,940 TWh (Figure 2.1).

A similar projection from the International Energy Association forecasts hydropower generation will rise to well over 7000 TWh by 2050. To achieve that level of hydropower generation indicates an increase of global hydropower capacity from 1,250 GW today to approximately 1,900 GW (Figure 2.2).[16] Based on average investment costs, this represents a total investment pool of nearly two trillion US$.[17] More than half of that capacity growth is projected to occur in Asia. Africa is forecasted to experience the greatest percentage increase, with capacity anticipated to nearly triple from 34 GW to 88 GW by 2050. Other projections have suggested that global hydropower capacity in 2050 could reach nearly 2,500 GW.[18] Although this increase in capacity will require thousands of new dams, note that there are two ways to increase hydropower generation without new dams. First, existing hydropower dams can be upgraded with new turbines and/or increased capacity leading to increases in generation.[19] Second, turbines can be added to previously non-powered dams, such as the addition of more than 300 MW of capacity added to navigation dams on the Ohio River.[20] The U.S. Department of Energy reported that 12 GW of capacity could be added to non-powered dams in the United States, a 15 percent increase to the country's conventional hydropower fleet.[21]

12 For example, voltage control and the ability to provide a "black start," which refers to restarting generation following a power outage without requiring an external source of power.
13 Though note that other mechanisms for storage, such as batteries, are growing faster than anticipated (Cardwell, 2017); sources such as Bloomberg's New Energy Outlook 2016 forecast a growing role for batteries providing grid-scale balancing for a projected large growth in variable renewables, particularly solar.
14 Montero and Perez, 2009.
15 Akhmatov, et al., 2007.
16 Note that IEA (2012) states that a global forecast for 2050 of 1950 GW but their breakdown by continent sums to 1850. In Figure 2.2 we show 1850 because we wanted to show projected growth by continent.
17 Assuming investment costs averaging 2.5 million US$ per MW of installed capacity; For example, Sovacool, et al., (2014) reviewed 61 hydropower dams with US$271.5 billion in construction costs constituting 114 GW, which is an average of 2.4 million US$ per MW.
18 World Energy Council and PSI, 2013.
19 HydroWorld, 2008.
20 Runyon, 2016.
21 U.S. Department of Energy, 2012.
22 Data for 2016 capacity are from International Hydropower Association (IHA). In this report, Asia encompasses Australia, Oceania and Russia, while Turkey is grouped with Europe. Latin America includes Mexico, Central America and South America. Current capacity includes both conventional and pumped storage (PS) hydropower to facilitate comparisons with 2050 projections that include PS.

FIGURE 2.2

Global installed capacity of hydropower in 2016 was 1,246 GW.[22] Based on an energy model that assumes a higher proportion of low-carbon energy sources, global installed hydropower capacity is projected to reach 1,850 GW (IEA, 2012; see footnote 16).



BOX 2.1
Types of hydropower projects

Hydropower projects can generally be classified into either "storage" dams—those that impound water for use during other times of the year—and "run-of-river" dams, in which reservoir storage is held constant and outflow equals inflow. "Pumped storage" is a third type of hydropower project which actively pumps water to store its potential energy and is primarily used for load balancing in energy systems.

Dams with storage reduce the variability of flows that otherwise can vary dramatically within a year, such as between a wet season and a dry season, and allowing a more consistent flow of water through the turbines (Figure 1). Large reservoirs are capable of storing water across years and can thus reduce variability between wet years and dry years. Storage reservoirs give hydropower managers the ability to release water into the turbines when energy is most needed or valuable, such as during the season of highest demand. Within a day, hydropower managers can release water into turbines to respond to rising demand or variable supply, a mode of operation known as "load following," or to meet short-term peaks in demand, known as "peaking."

Run-of-river dams are generally considered to have a lower impact on rivers systems because they don't alter the overall flow pattern, but the actual operation associated with the term "run-of-river" can differ by region, resulting in very different impacts. In some regions, run-of-river balances instantaneous outflow and inflows from dams. However, in other regions, run-of-river can refer to a project that stores water within a day, and inflow equals outflow on the basis of the daily average. This mode of operation can allow the storage of water for, say, twenty hours, with no or minimal flow release below the dam, and then a release of high flow for four hours during periods of peak demand. Although the daily average flow would be the same above and below the dam, the river below the dam experiences 20 hours of near-drought conditions followed by four hours of near-flood conditions each day.

Pumped storage is an energy storage system in which water is pumped uphill during periods when energy is readily available and inexpensive. The higher-elevation reservoir then stores the water as potential energy that can be dispatched when needed by allowing the water to flow back downhill through turbines. Pumped storage is the most important type of energy storage in energy grids worldwide. Overall, the pumped-storage process is 70-85 percent energy efficient. The environmental impacts of this pumping and rapid fluctuations can be minimized by siting the pumped-storage system between two reservoirs, or even completely off-stream, as opposed to an upper reservoir drawing from, and then discharging to, a river.

Hydropower dams can also be differentiated as being single purpose, in which energy is the only major management objective of the dam, and multipurpose, in which the dam is managed for other objectives, including water supply, irrigation and flood-risk management—a set of functions that require the dam to provide storage of water. A recent analysis of a database of the International Commission on Large Dams reported that of the approximately 10,000 hydropower dams globally, 60 percent are single purpose and 40 percent are multipurpose.[23] However, it should be noted that dams which are managed with power as their only major objective (single purpose) can and do have additional functions and effects on the local economy such as tourism, fishing and even flood attenuation. The useful contributions of hydropower to the efficiency of a transmission system such as the rapid ability to start and stop generating mean that almost all hydropower is managed with the objective of improving grid stability, not solely maximizing generation.

Global assessment of water-management services within hydropower influenced basins

In addition to energy services, hydropower projects often serve multiple other purposes, including providing water storage for drinking water supply, irrigation and flood-risk management (see Box 2.1).[24] Interactions with these water-management services does not apply only to multipurpose dams. Even single-purpose hydropower projects are planned for, or operate within, river basins with demands and expectations for these water-management benefits. Hydropower development is thus influenced by demands for these other services and hydropower operations interact with these other sectors in ways that can be negative, neutral, or positive for these sectors.

To understand the potential scope of these interactions, we quantify water-management services within all those river basins in the world where hydropower does—or will—strongly influence water use and river functions. Within this global set of "hydropower-influenced basins" (HIB) we provide quantitative estimates of the values of water supply, irrigation and flood-risk management services. This global roll-up provides an estimate of the scope of economic values that could be impacted negatively by hydropower (e.g., through dams not planned in coordination with broader basin objectives; Chapter 3) or, conversely, the scope of economic values that could benefit by system-scale planning and management of hydropower and other infrastructure (Chapter 4).

To derive a set of HIB, we used a global data source where the Earth's surface is divided into 1,342 river basins and sub-basins[25] and two global databases of dams: one that provided existing hydropower dams;[26] and one of hydropower dams that are either currently under construction or in the planning process ("future hydropower dams").[27] For the purposes of identifying HIB, we combined current hydropower dams with future hydropower dams and selected those basins where hydropower either does, or will, exert a major influence on rivers and water within the basin.[28]

Among the 1,342 basins, 441 were classified as HIB. For illustrative purposes, we placed these 441 basins within four categories, based on two basic characteristics (Figure 2.3):[29]

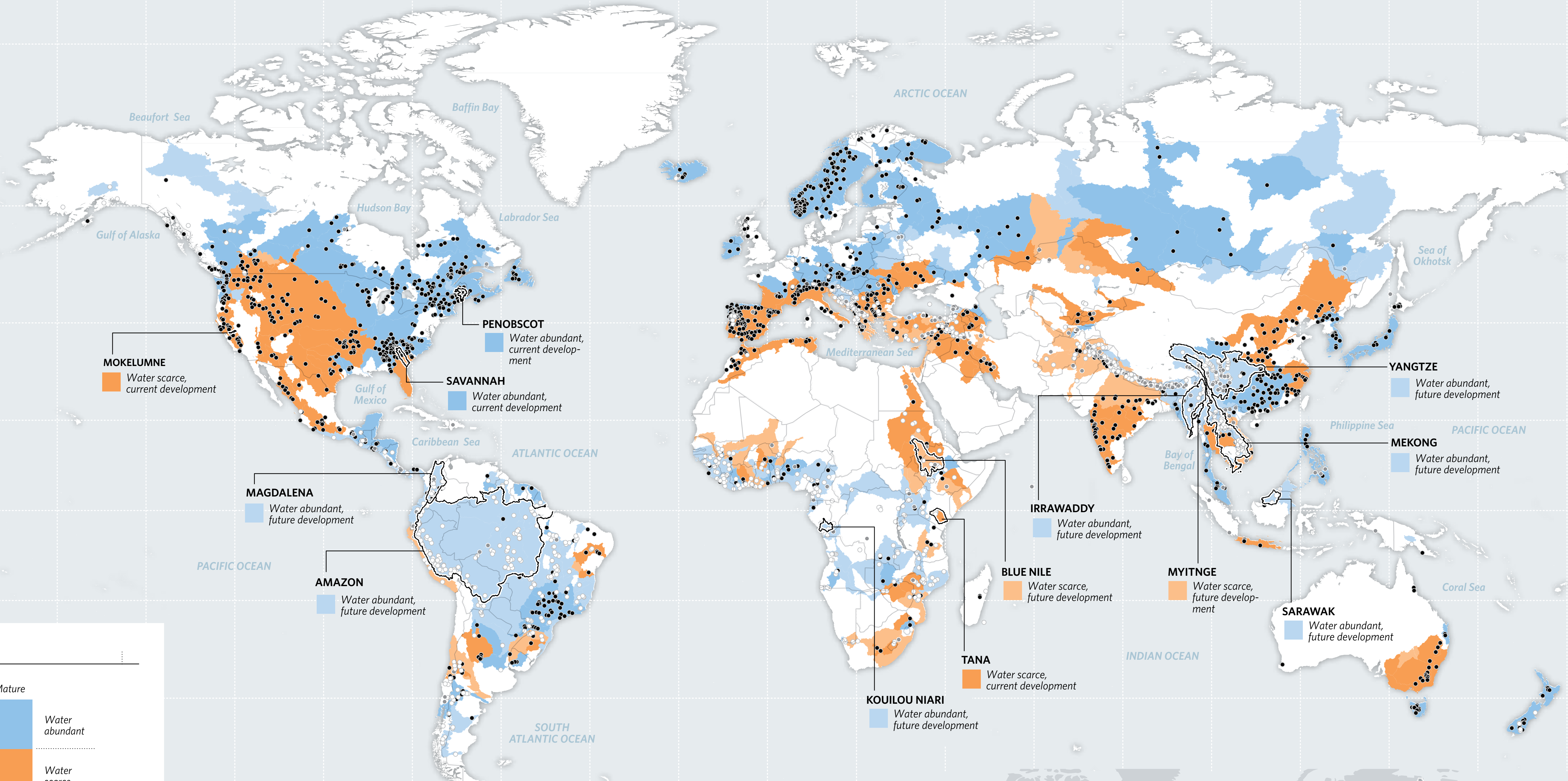
- Level of development, ranging from basins where all hydropower development is in the future to those where all hydropower development that will happen has already happened.
- Level of competition for water, ranging from basins with abundant water year-round to basins where water is scarce and/or flows are highly irregular. In the former basins, hydropower will more likely be single purpose and in the latter, the need for storage (e.g., for irrigation) will tend to be greater. In water-scarce basins, dams with hydropower will often be multipurpose, and single-purpose hydropower dams will exist within a system of infrastructure that includes storage and management for multiple purposes.

Based on these two axes, the four categories are:

1. Current development, water abundant
2. Current development, water scarce
3. Future development, water abundant
4. Future development, water scarce

The economic drivers, constraints and opportunities are all likely to vary among those four basic categories. For example, strategic planning and management can influence dam siting and design far more easily within "future development" basins. Within "current development" basins, design can only be influenced through retrofits and location can only be influenced through dam removal. Within "water abundant" basins, there may be limited or no pressure for hydropower dams to contribute to storage for irrigation and the primary tradeoffs and opportunities to manage may revolve around environmental and social resources. For example, dams in the Amazon are generally single purpose hydropower dams and thus the primary tradeoffs include environmental values, such as fisheries, and social values, such as indigenous land.[30] In water-scarce basins, on the other hand, dams—either as an individual project or as an overall system of infrastructure—are more likely to provide a broad range of services, including hydropower, flood-risk management and storage for water supply and irrigation.

23 Branche, 2015.
24 Branche, 2015.
25 Lehner and Grill 2013
26 Global Reservoirs and Dams (GRanD); see Lehner et al., 2011.
27 Zarfl et al., 2015.
28 A combination of total MW, fragmentation and alteration of flows; see Appendix E.
29 See "Global spatial analysis" within Appendix E.
30 Note that navigation is a purpose of some dams in the Amazon.



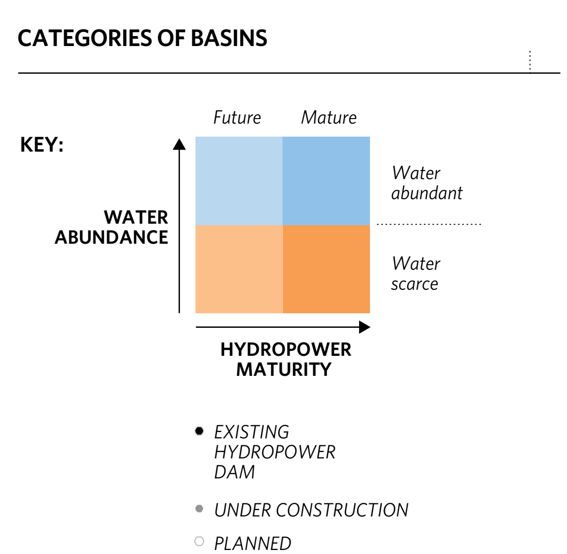
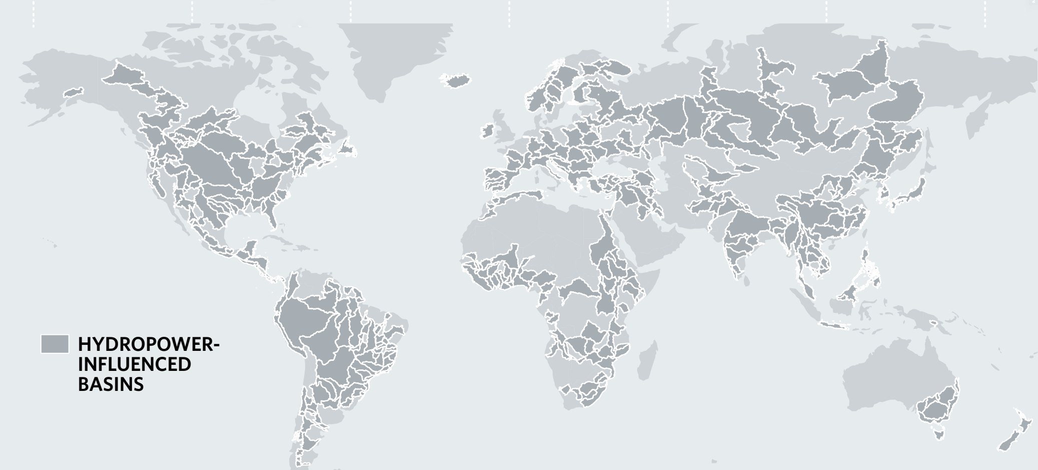


FIGURE 2.3

Hydropower influenced basins; blue shading indicates those with abundant water; dark blue are "mature" in terms of development ("current development") and light blue have most development in the future. Orange shading indicates area where water is more scarce; dark orange are "mature" ("current development") and light orange have development in the future. Solid dots are existing hydropower dams, gray dots are hydropower dams under construction and open circles are planned or potential hydropower dams. Case study basins are highlighted.



Environmental and social values will also be part of this complex set of management expectations. The case studies in this report all fall within this categorization (Figure 2.3 and Figure E1 in Appendix E).

The HIB encompass 1,200 GW of current installed capacity of hydropower. Dams under construction and in the planning pipeline could bring that total to approximately 2,000 GW (Figures 2.4 and 2.5).[31] The "current development, water scarce" basins have the highest human population (nearly 1.5 billion), followed by the "current development, water abundant" basins with 1.1 billion. The two categories of "future development" basins encompass similar total human population (approximately 800 million people each).

We then used global databases to quantify the total levels of the following water-management services within these four broad types of basins:

Water-management services

- Irrigation: Hectares of irrigated land.
- Water supply: Volume of water stored in reservoirs for water supply (for domestic and industrial uses).
- Flood-risk management: Within urban areas, the number of people and extent of real estate at risk of flooding; we focused on urban areas because although rural areas can suffer from damaging floods, rural areas may also include people who benefit from river flooding (e.g., floodplain fisheries and flood recession agriculture).

The total economic value of water-management services within HIB is very large, estimated to be between US$285 and US$770 billion per year:[32]

- 180 million hectares of irrigated land (Figure 2.6), providing between US$100 and US$410 billion in annual economic value.
- 660 million people and 145,000 square kilometers at risk of flooding within urban areas (Figure 2.7); annual flood damages within the HIB range from US$20 to US$40 billion and can be interpreted as the potential value of flood management.[33]
- 88,000 million cubic meters (MCM) of reservoir storage for water supply, sufficient to support approximately 600 million people with drinking water, with a potential economic value between US$160 and US$320 billion (Figure 2.8).[34]

FIGURE 2.4

Hydropower capacity within the four types of basins. Blue represents existing hydropower; orange is future (under construction and planned). The text GW label in each quadrant represents total capacity if all under construction and planned dams were completed and added to existing hydropower dams.

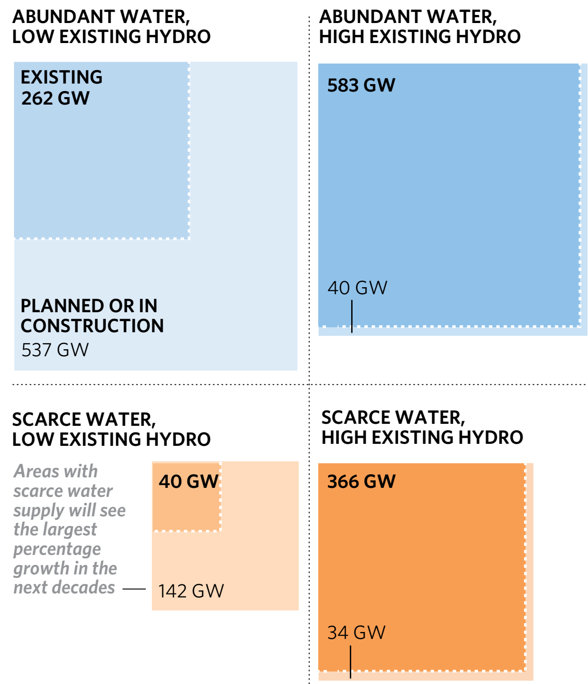
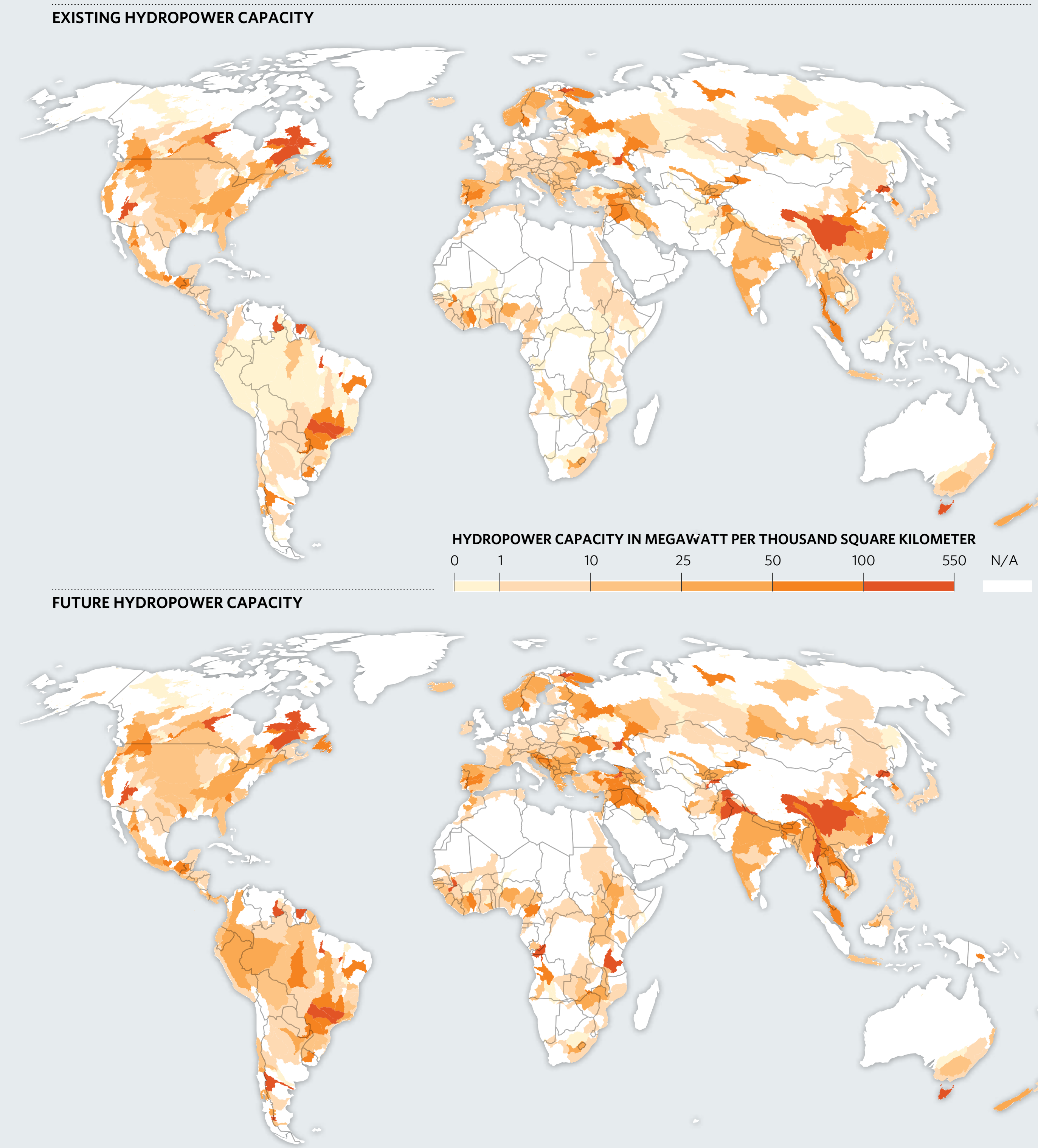


FIGURE 2.5

Hydropower influenced basins shaded to reflect basin capacity of existing hydropower dams (top) and total basin capacity after completion of under-construction and planned dams, adding to existing capacity (bottom). Because the basins encompass a broad range of geographic area, capacity was divided by area and is reported in MW per thousand square kilometers of basin area.



31 Note that the "future" dams database undoubtedly contains many dams that will ultimately not be built and does not include many dams that may get built. It can be viewed as a sample of where dams are likely to be built.
32 See "Estimating Economic Value" within Appendix E for how these levels and economic values were estimated.
33 Here we assume that this annual damage represents the potential pool of economic value possible through flood-risk reduction management actions.
34 Assumes an average use of 200 liters per day per person.

FIGURE 2.6

Hydropower influenced basins shaded to reflect the proportion of their area equipped for irrigation from surface water sources.

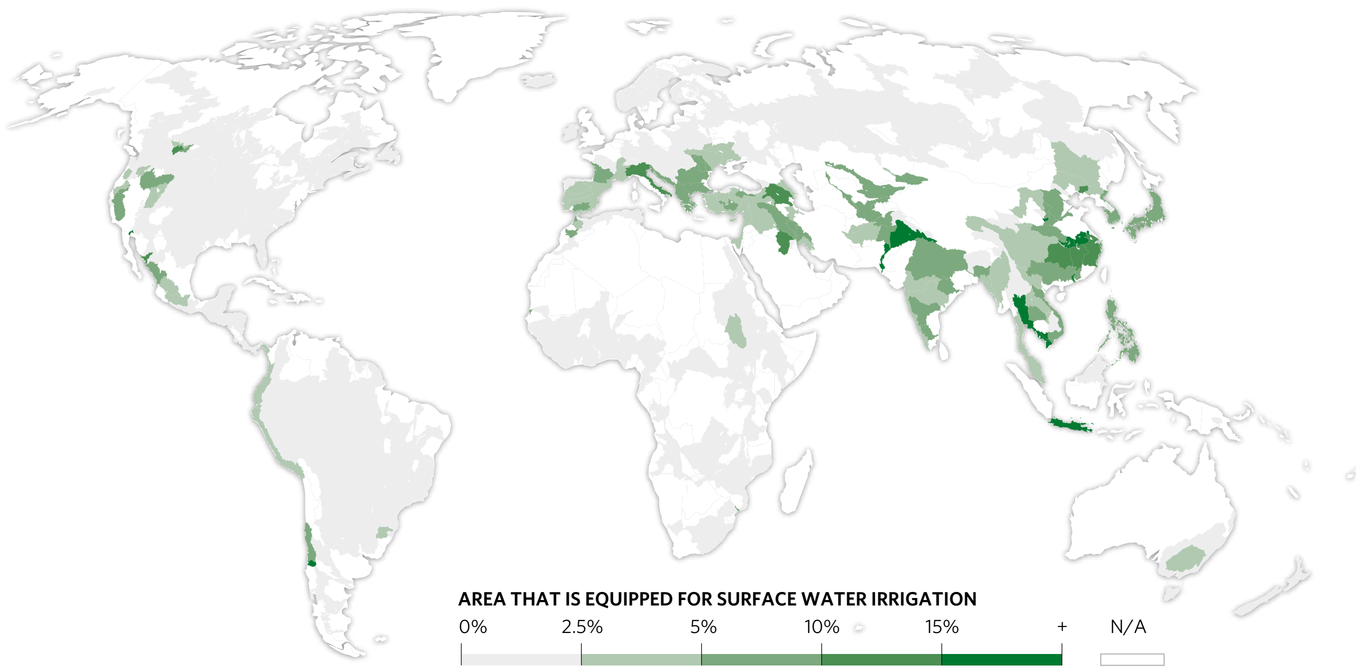
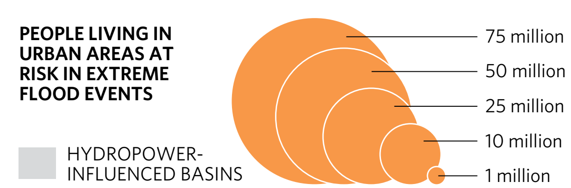


FIGURE 2.7

The number of people living in urban areas at risk of extreme flooding within hydropower influenced basins.



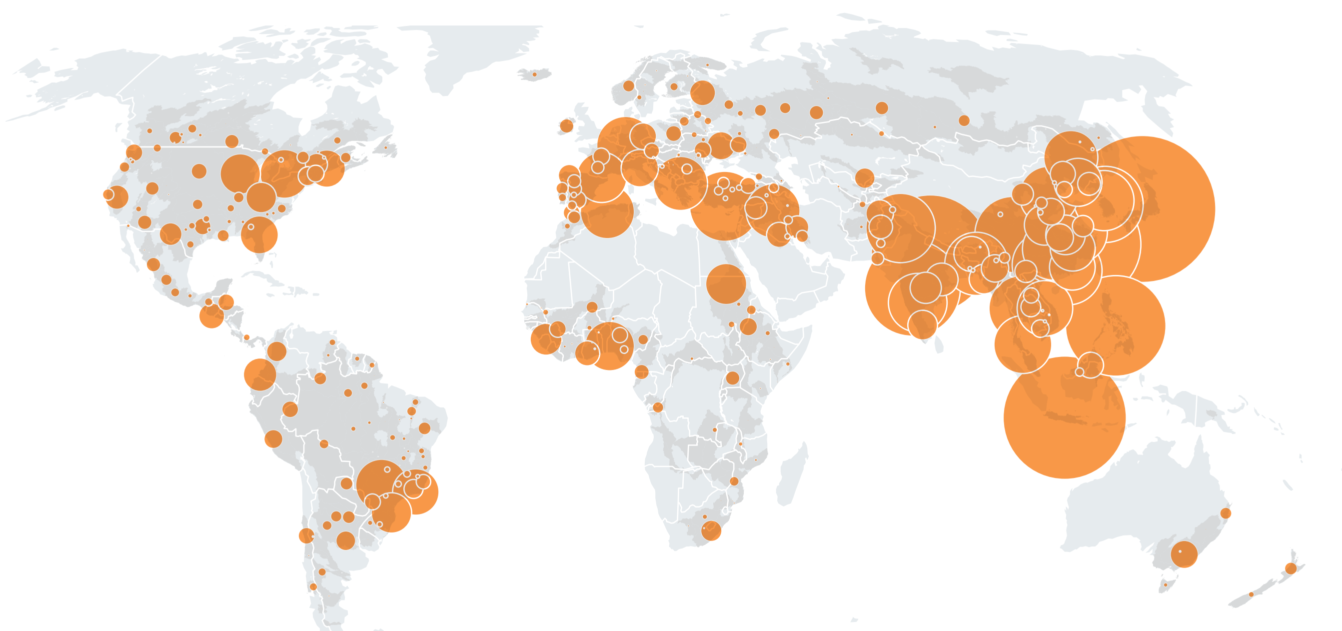


FIGURE 2.8

Hydropower influenced basins shaded to reflect extent of storage for water supply within reservoirs. Because the basins encompass a broad range of geographic area, storage was divided by area and is reported in MCM per thousand square kilometers of basin area.

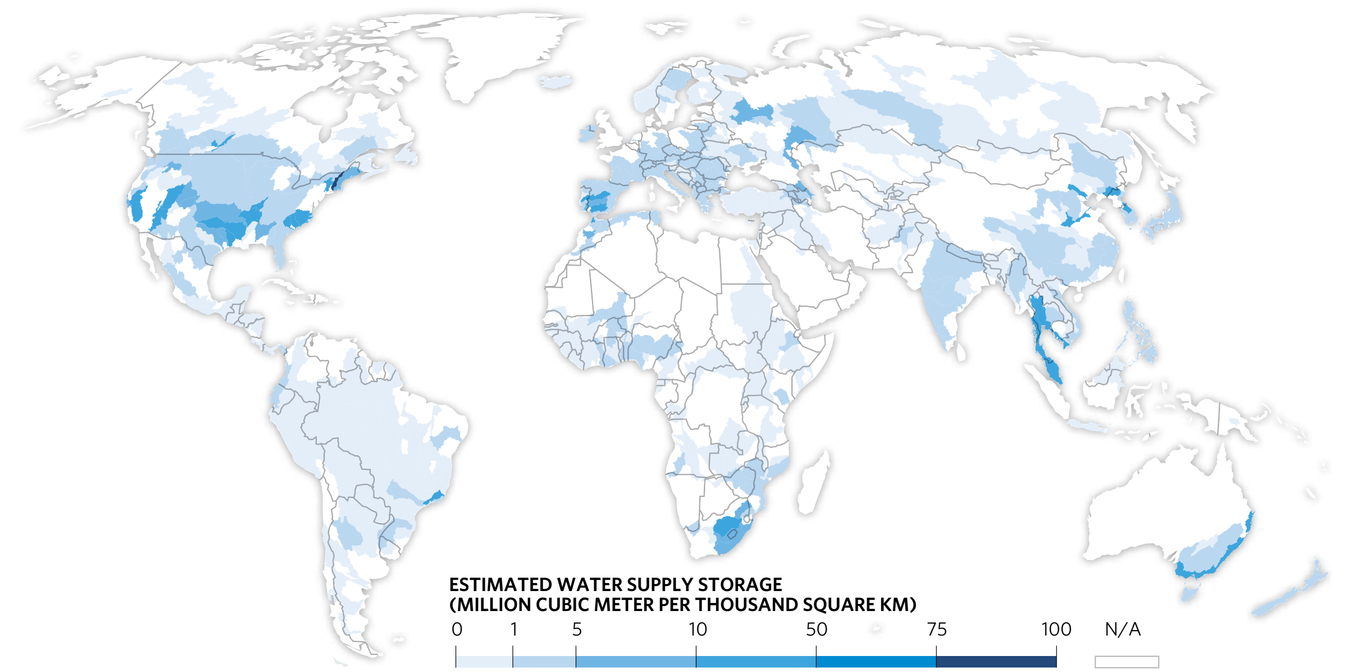


FIGURE 2.9

Levels of water supply storage, people at risk of flooding in urban areas, and hectares of land irrigated by surface water compared across the four types of hydropower influenced basins.

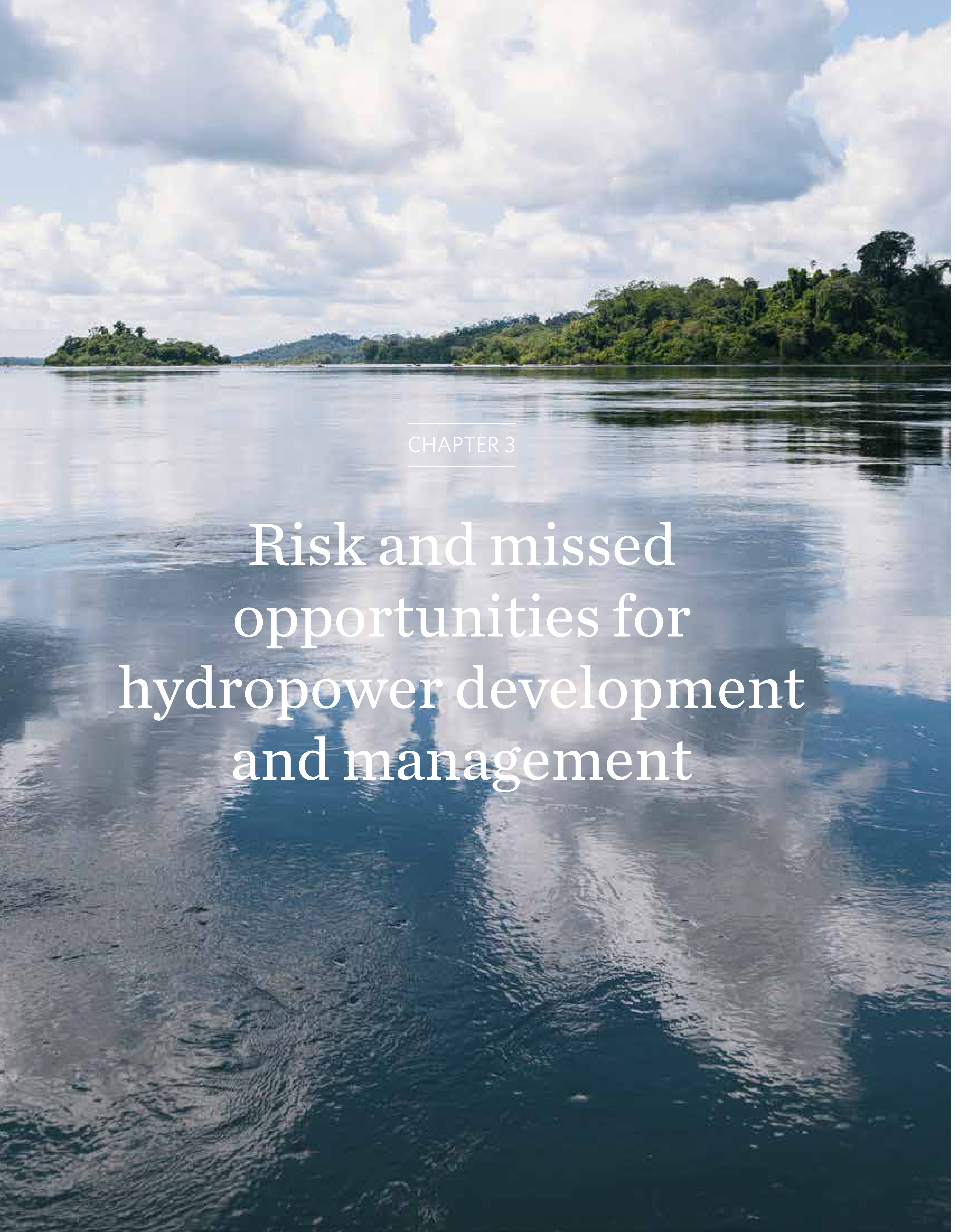
("future" = "future development"; "current" = "current development"; "abundant" = "water abundant"; "scarce" = "water scarce").

BASIN TYPE	WATER SUPPLY STORAGE (MCM)	FLOOD RISK (MILLION OF PERSONS)	IRRIGATED LAND (HA)
FUTURE ABUNDANT	888	70	16
CURRENT ABUNDANT	42,317	238	22
FUTURE SCARCE	6,531	97	53
CURRENT SCARCE	38,157	256	88

Globally, water supply storage and urban dwellers at risk of flooding are greatest within the two categories of "current development" basins, with roughly similar levels. As expected, there is relatively limited irrigation acreage within the "water abundant" basins. Among the "water scarce" basins, the "current development" basins have considerably more irrigated acreage than the "future development" basins. Thus, between the four categories of HIB, there appears to be roughly similar demands for water supply and flood management within both types of "current development" basins, while demand for irrigation storage is primarily within the "water scarce" basins.

Hydropower projects represent major infrastructure investments that can provide significant water and energy benefits to support development goals and economic activities. However, the dams and reservoirs necessary to generate these benefits can also cause considerable negative impacts to social and environmental resources.[35] Ensuring that hydropower development is done in a way that achieves balanced and equitable outcomes across these benefits and resources is the focus of the rest of this report.

35 Branche, 2015



CHAPTER 3

Risk and missed opportunities for hydropower development and management

© KEVIN ARNOLD (XINGU RIVER, BRAZIL)

In the previous chapter, we highlighted the energy benefits that hydropower provides and the water-management services that interact with hydropower planning and management within river basins. Demands for these energy and water benefits are spurring the major expansion of dams around the world, including a projected increase of approximately 600 GW of installed capacity in hydropower by 2050. While hydropower expansion and operation contribute to meeting important development and economic goals, if not done carefully they can lead to a wide range of interacting risks. Hydropower dams can cause considerable negative impacts on social and environmental resources. Economic risks arise where these environmental and social impacts degrade resources that underpin food, livelihoods and other resources valued by people. Economic risks also arise through infrastructure decisions that meet a narrow set of objectives but miss opportunities to provide broader benefits to a country. Finally, these negative impacts and missed opportunities can lead to social conflict and regulatory uncertainty—and added costs for mitigation requirements—posing financial risk for developers and investors. This chapter reviews these various forms of risk.

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(BOCAS DE BARBACOAS, MAGDALENA RIVER, COLOMBIA)

CHAPTER 3 KEY POINTS

- River basins that are, or will be, influenced by hydropower support a range of important environmental and social resources, including:
    - At least six million tons of fish harvested from rivers (83 percent of global harvest of riverine fish), enough to feed at least 130 million people and employ 50 million people.
    - More than half of all freshwater fish species on Earth.
    - The majority of flood-recession agriculture.
- Hydropower can cause negative impacts to these and other environmental and social resources. While project-level sustainability has improved, many of these impacts are difficult or impossible to mitigate at that scale. A large majority of future hydropower expansion will occur in river basins with highest fisheries productivity and highest diversity of fish species.
- If not carefully planned and managed, infrastructure investments and water-management operations—including hydropower—can interfere with each other. Further, without a system approach, hydropower investments may not fulfill their potential to contribute to other strategic energy and water needs.
- Due to these impacts and missed opportunities, hydropower can trigger social conflict, contributing to delays and cost overruns and sometimes cancellations. Hydropower has a higher frequency and magnitude of delays and overruns compared to other large infrastructure projects.
- In the past five years, environmental and social concerns have contributed to several high-profile project cancellations, representing an aggregate of 1.3 billion US$ in stranded investment and 18 GW capacity not developed.

© JEFF OPPERMAN/TNC (ASIAN REDTAIL CATFISH AT FISH MARKET IN LAOS)

Environmental and social resources

The projected buildout of hydropower dams could negatively impact more than 300,000 kilometers of river channel worldwide.[36] These impacts include conversion of river channel to reservoir, fragmentation, sediment trapping and flow alteration. Hydropower's environmental and social risks, and their associated economic impacts, have been well documented elsewhere[37] and we provide a summary of those issues in Appendix C. Here, we explore the scale of environmental and social resources at stake within hydropower-influence basins (HIB), similar to the analyses for water-management services in the previous chapter. Below we provide estimates for the level of fish production, fish species diversity and flood-recession agriculture within basins influenced by hydropower. For environmental and social resources, we were able to quantitatively estimate global levels for:

Fisheries: The HIB support 6 million tons of fish harvested each year, which is 83 percent of global harvest from rivers. This harvest can provide sufficient protein for more than 130 million people (Figure 3.1). Additionally, inland fisheries provide livelihoods for approximately 60 million people (both in harvest and processing), with 55 percent of that number composed of women.[38] Scaling that to the proportion of global fish harvested, this suggests that river fisheries within the HIB provide employment for 50 million people.

Biodiversity: At least 7,150 species of fish, more than half of all freshwater fish species on the planet, occur within HIB (Figure 3.2).

The fisheries harvest estimate is almost certainly an underestimate. The data we used are based on country-reported harvests to the Food and Agricultural Organization (FAO) and freshwater fish harvests are generally known to be underreported. For example, the country-level data for countries in the lower Mekong basin (LMB) is less than one-third of the level that studies from the Mekong River Commission have found when they have sought to be more comprehensive than typical market measures of harvest or sale.[39] These studies report a total of 2.3 million tons from capture fisheries in the LMB with an estimated economic value of US$11.2 billion, with 5 million people taking part in fisheries activities.[40] Other regions of the world also underreport production. If we conservatively assume that actual production is 50 percent higher than reported, then the HIB would support at least 9 million tons of fish providing protein to at least 195 million people.

36 Opperman, et al., 2015a.
37 WCD, 2000; Scudder, 2005; Postel and Richter, 2003; Ligon, et al., 1995; Vörosmarty, et al., 2010.
38 UNEP, 2010.
39 FAO country-level data for lower Mekong are 714,000 tons and are based on registered landings of fish harvest. The Mekong River Commission uses consumption data and estimates fish production at approximately three times greater, 2.3 million tons.
40 MRC, 2015.

FIGURE 3.1

Hydropower influenced basins shaded to reflect estimated amount of fish harvest from rivers and their floodplains.

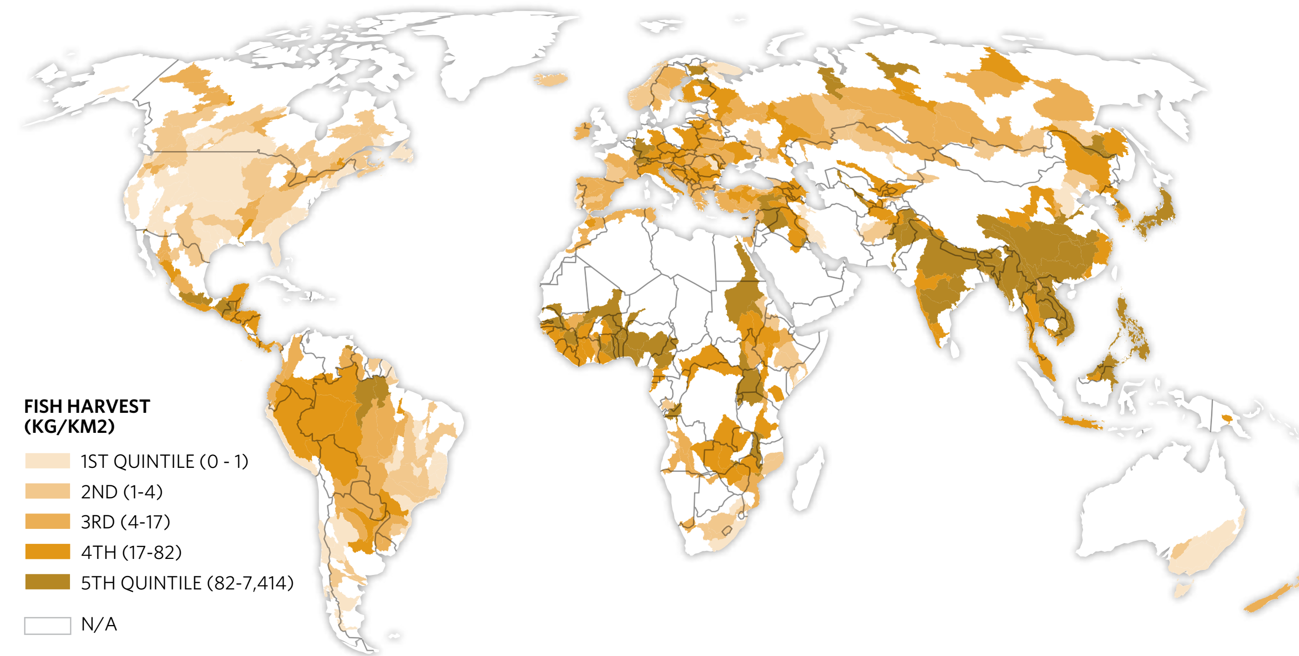
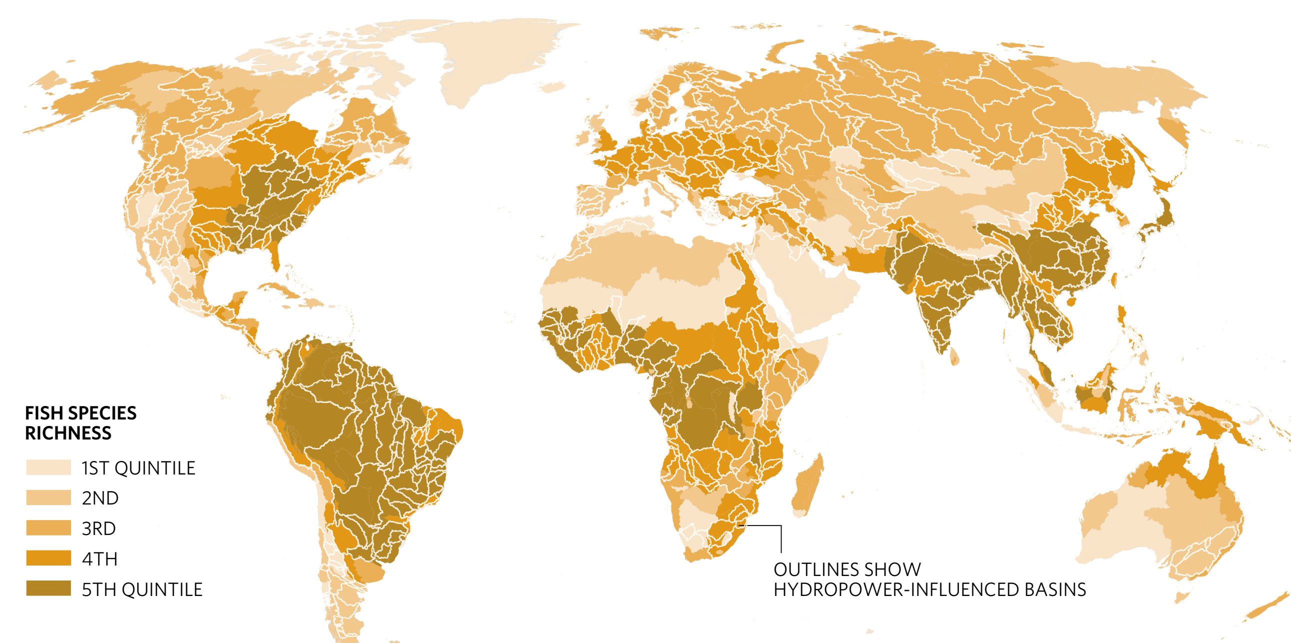


FIGURE 3.2

Hydropower influenced basins shaded to reflect species richness of fish.



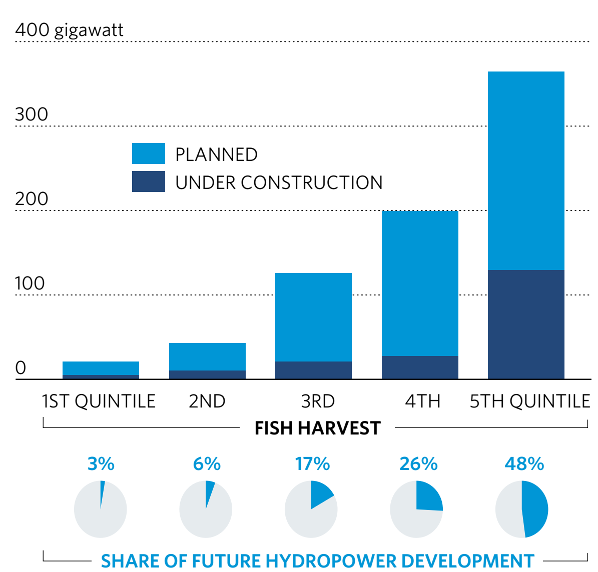
Global data on flood-recession agriculture, or flood-based farming, do not exist. However, estimates suggest that there are 25 million hectares of flood-recession agriculture in Africa alone, and this form of food production is also very important in many countries in Asia, including Bangladesh, Cambodia, India, Laos, Myanmar, Nepal and Vietnam.[41] Most of the rivers that are commonly highlighted as being important for flood-recession agriculture are within the set of HIB in both Asia (e.g., Ganges, Irrawaddy and Mekong) and Africa (e.g., Niger, Omo, Senegal and Tana) and most of these are in basins where hydropower is projected to expand. Thus, it is likely that the majority of important areas for flood-recession agriculture are within the HIB and most of those mentioned above are within the future development basins. Similarly, about 70 percent of new hydropower expansion is expected to occur in those river basins that support the highest diversity of fish species[42] and 75 percent of all new hydropower is projected for the river basins within the top two quintiles in terms of fish productivity (Figure 3.3).

Thus, the large majority of future hydropower growth will occur in those river basins that have the greatest linkage between healthy rivers and people's food and livelihoods and that support the highest richness of aquatic species.

In addition to the ecosystem services described above, hydropower development and management have impacts on a wide range of social values and resources. Many of these are positive, as projects contribute to employment, improved roads and electricity services, local taxes and royalties as well as other benefits. Multipurpose projects can have major socio-economic benefits in the form of water supply and flood-risk management. However, while some groups benefit, other groups may experience negative impacts. Negative impacts are most likely to affect traditional rural societies and indigenous communities that depend on rivers for livelihoods and food as well as those who are displaced by dams or reservoirs. Displacement can be physical, such as inundation of a community, or economic, such as the loss of livelihoods due to altered downstream fisheries and/or flow patterns. The poorest people are most likely to depend on access to land and natural resources, such as fisheries and riverbank gardens, and are most vulnerable to social change.[43] In high income countries, common environmental and social concerns include the loss of wilderness, free-flowing rivers or cultural landscapes, and impacts to associated biodiversity, aesthetic and recreational values. However, even in higher income countries, river restoration can promote social, cultural and economic resources valued by indigenous people, such as the planned removal of four hydropower dams on the Klamath River (California, USA)[44] and the dam removal that has already occurred on the Penobscot River (Maine, USA; see case study in Chapter 5).

FIGURE 3.3

The amount of under-construction and planned hydropower within each quintile of fish fishery production among hydropower influenced basins (with one being the lowest and five the highest harvest). Nearly half of all future hydropower is projected to occur within the basins that are in the highest quintile of production; three-quarters of future development is within the top two quintiles combined.



41 Spate Irrigation Network Foundation.
42 Opperman, et al., 2015a.
43 Scudder, 2005.
44 The Mercury News, 2016.

Challenges with addressing environmental and social impacts at the scale of individual dams

While some of the environmental and social impacts described above (and in Appendix C) can be addressed through site-specific actions, many cannot. A wide variety of constraints can limit the ability for restoration or mitigation to occur at the scale of a single dam and some impacts are nearly impossible to mitigate at that scale. For example, techniques for passing sediment through a reservoir, or mitigating downstream effects of sediment capture, are very difficult and expensive and generally require ongoing management.[45] Tall dams generally create long reservoirs and most sediment the size of sand or larger is deposited at the head of the reservoir, far from the dam and the downstream reach of flowing river. Moving that sediment through such reservoirs is only possible with extremely expensive solutions, such as dredging and barging, although sediment below a certain size can be moved through a slurry pipeline.

Effective fish passage can also be extremely difficult or impossible to achieve with dams above a certain size, or for certain species of fish. Many commercially important fish species do not use fish ladders and even for those species that do, dam passage can impose stress and increase mortality of migrating fish.[46]

Flow alterations can be addressed through the release of environmental flows.[47] In Cameroon, a dam on the Logone River, forming Lake Maga in 1979, had negatively impacted floodplain-dependent communities by diminishing the extent of annual flooding. The dam released experimental floods intended to re-inundate the floodplain and restore economic activities such as grazing and fishing.[48] In the area flooded experimentally, cattle numbers increased 260 percent.[49]

However, for existing dams, physical constraints of the dam, such as the size of outlets, can often limit the ability to release flows necessary to maintain downstream ecosystems (e.g., a flood pulse capable of inundating floodplain wetlands). Further, the economic purposes for which the dam was built can also limit the range of environmental flows that can be released, for example, where the release of environmental flows would result in too much water being "spilled" and not passing through turbines leading to excessive loss of revenue for the dam operator.

Water quality impacts can also be addressed through dam operations but, again, for existing dams, this requires that the dam design be capable of these operations. For example, multi-level outlet structures can allow dam operators to manage the temperature of the water they release.[50] However, if the dam were not built with this capacity, mitigating temperature impacts can require an expensive retrofit (e.g., US$80 million for a multi-level outlet structure retrofit on Shasta Dam on the Sacramento River, California, USA).[51]

The constraints on single-project mitigation are perhaps most obvious for environmental impacts. But social mitigation can also be ineffective at the level of the individual project. There can be cumulative impacts from several projects that can only be effectively addressed through a regional development strategy. Social conflicts can arise easily if displaced people move into unprepared or antagonistic host communities and encounter difficulty reestablishing livelihoods.

These potential limitations of and constraints for mitigating impacts at the scale of an individual dam suggest three observations:

- Dam design is critically important for its environmental and social performance. For example, variably sized turbines may allow hydropower dams to operate more efficiently over a wider range of discharges, thereby providing greater flexibility to release variable environmental flows with lower impacts on generation and revenue.[52] Other important design considerations include oversizing outlet capacity and multiple-level outlets that can provide greater management flexibility for water quality and temperature. These design solutions are almost always far more affordable during original design than as a retrofit.

45 Kondolf, et al., 19
46 Agostinho, et al., 2008.
47 harme, 2003.
48 Loth and Acreman, 2004.
49 Moritz, et al, 2010.
50 Cassidy, 1989.
51 Sherman, 2000.
52 Balc and Ždankus, 2007.

- The location of a dam is generally the most important influence on how it will impact environmental and social resources. In a 2003 World Bank report, Ledec and Quintero emphasized that good site selection is by far the best "mitigation" strategy for dam development: avoiding or minimizing impacts through comprehensive site selection can greatly reduce the need to mitigate impacts through design and operation.[53] Comprehensive site selection can ensure that new dams avoid locations that will have the greatest impact on resources such as migratory fish or sediment transport.[54] Site selection can also help new reservoirs avoid locations where upstream land use will contribute nutrient loadings that lead to high rates of methanogenesis in the reservoir.[55]
- Moving toward a system scale may reveal a broader set of solutions for overcoming constraints, achieving meaningful environmental benefits and balancing the objectives of energy, water management and environmental health. As illustrated by the case studies later in this report, the benefits of a system-scale approach pertain to both planning of new dams and "re-optimizing" existing dams or systems of dam—as well as looking more broadly across options to deliver energy and water services to identify non-dam solutions.

Hydropower's interactions with other water-management sectors

Hydropower is a major user of water and, particularly in arid environments, can also be a major consumer of water through evaporation from reservoirs.[56] Major rivers in arid climates, such as the Colorado, Nile and Zambezi, may lose 10-20 percent of their water to reservoir evaporation.[57] As a user and consumer of water, hydropower interacts with other water-management sectors in a river basin. Further, individual hydropower projects are often built as multipurpose infrastructure to deliver other water-management services including water supply, irrigation, navigation and flood-risk reduction.

Dams can be described as being "single purpose" or "multipurpose" (Box 2.1). Many hydropower dams have the single purpose of energy generation, although regulations can require dams with an initial sole management purpose of hydropower to also manage for environmental health and recreation. Single purpose hydropower dams are most common in high elevation, mountainous river reaches. Very large dams with storage are often multipurpose. For example, the largest dams in the US were built by agencies with a primary purpose of either water supply (e.g., the U.S. Bureau of Reclamation and the California Department of Water Resources (DWR)), or for navigation and flood control (dams built by the U.S. Army Corps of Engineers). The largest of the dams built by these entities are generally multipurpose and include hydropower, such as Hoover (Reclamation), Oroville (DWR) and Grand Coulee (the Corps) dams. In many cases, the revenue generated by hydropower is used to subsidize multipurpose dams that provide benefits, such as water supply and flood management, that do not provide direct revenue streams.

Within multipurpose dams, the various uses can compete with each other for the allocation of storage and for flow releases at various times. For example, the ability to manage floods improves with decreasing reservoir levels, with the empty storage space available to capture and attenuate incoming flood flows, whereas full reservoirs reduce risk of drought for water-supply functions. Hydropower generation is a function of flow and head and so a full reservoir, with greater head, generates more energy. However, full reservoirs tend to "spill" more water (water that passes over spillways and thus does not go through a turbine), so hydropower managers try to manage reservoirs to minimize spill. Within multipurpose reservoirs, climate change has the potential to increase the conflicts between the multiple purposes (described in more detail in Appendix D).[58]

These multiple purposes can interact and compete at the scale of a single dam or within a system of infrastructure in a river basin or region. In the absence of strategic planning, major infrastructure investments, including dams, may even interfere with each other, compromising performance of individual investments (see Box 3.1). The developers of the two large projects on the Madeira River in Brazil have been in conflict because a high water level in the lower Santo Antonio reservoir can impact generation from the upper Jirau project.[59] The expansion of irrigated agriculture in the Great Ruaha basin, upstream of Tanzania's main hydropower projects, has led to reduced flows and major challenges for power supply security in Tanzania.[60]

53 Ledec and Quintero, 2003.
54 Opperman, et al., 2015a.
55 Deemer, et al., 2016;
56 Mekonnen and Hoekstra, 2012.
57 See SADC-WD and Zambezi River Authority, 2008; U.S. Department of the Interior Bureau of Reclamation, 2016.
58 Lee, et al., 2009; Branche, 2015.
59 Hartmann, et al., 2013.
60 McCartney, et al., 2007.

In addition to direct conflict between projects, development not guided by strategic planning can result in projects that fall short of their potential to meet broader goals or even increase the challenge for meeting those goals. For example, developers may propose a run-of-river dam rather than a storage dam (because run-of-river are generally easier to fund and build) at a site where water storage would provide significant benefits to a country (e.g., water storage for irrigation or for energy services). Once that site has been developed for a run-of-river project, the country may then need to find a different site for storage and find investment for an additional project. Meanwhile opportunities for synergies were missed and, potentially, some advantageous options have been foreclosed.

We note that there are several reasons why development decisions within countries may underperform in terms of achieving broader strategic purposes. These include lack of budget or capacity within government agencies, governance issues, or simply the extreme urgency for meeting electricity demand coupled with a perception that strategic planning is slow. As described in the next chapter, this report provides suggestions and examples of how new modeling tools can increase the speed of strategic planning and how the integration of various tools can facilitate the identification of development options that are both economically strategic and financially attractive.

We also emphasize that we are not suggesting that, to be strategic, hydropower investments should always be multipurpose and/or include storage. Adding additional purposes to a dam primarily to gain political support, not because the project is the most effective means to deliver those purposes, also erodes the strategic value and benefits of infrastructure investments. For example, adding flood management responsibility into a hydropower project can reduce annual generation and thus should not be added unless a system-planning approach has demonstrated the strategic value of adding that purpose (see Box 4.4).

As described below, system-scale planning and management can reduce conflicts and maximize synergies between water-management services. Planning can seek to optimize infrastructure investments to achieve multiple benefits from a system while, even within a well-planned system, ongoing management (e.g., within a reservoir or cascade) may be needed to continue to balance objectives.

BOX 3.1
Competition Between Water-Management Objectives in the Maipo River in Chile

An example for the complexities of water resources management is the Maipo River in Chile, the major source of water for seven million people in the Santiago metropolitan area, as well as for 136,000 hectares of high-value irrigation, a growing hydropower sector, and other water-related activities such as kayaking and rafting. Droughts and high turbidity contribute to the challenges of regional water management. Siting and design of the latest hydropower project, the 531 MW run-of-river Alto Maipo project, has aimed to reduce the impacts on other sectors, but has also shown that some water uses in the basin are not compatible with each other. For example, plans by the water supply company to draw drinking water from a high-altitude reservoir would reduce the power generation potential and peaking power generation may impact on water users downstream. In the absence of an overall basin development plan, the assignment of water rights and the planning and permitting of infrastructure projects has proceeded in a piecemeal manner, with some bilateral deals between water rights holders but also legal conflicts. And in the absence of a country-wide hydropower masterplan, the developer chose a project close to Santiago instead of a project in a more remote region with fewer water resource complexities.

Impacts and missed opportunities lead to conflict and investment uncertainty

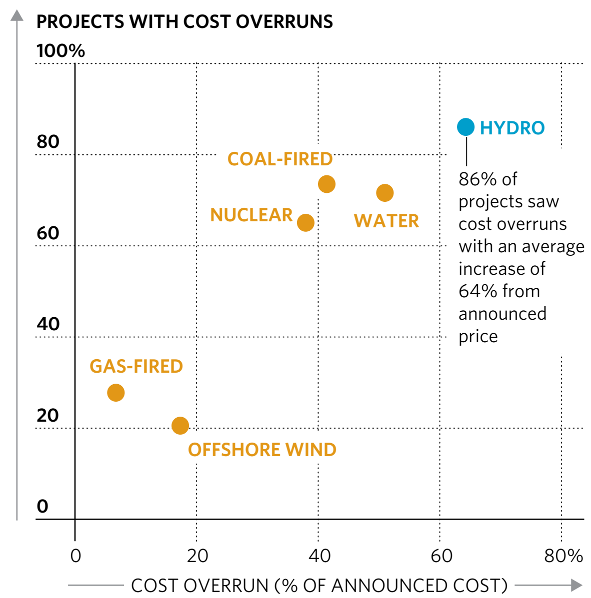
These environmental and social impacts can contribute to conflicts that delay projects or even lead to cancellation. In the past five years, several high-profile projects have been suspended or cancelled, including Myitsone in Myanmar (6 GW; suspended after US$800 million had been invested), [61] HidroAysén in Chile (2.75 GW; US$320 million invested),[62] and São Luiz do Tapajós in Brazil (8 GW, US$150 million invested). These are estimates of "sunk investment costs," but estimates may be contested by various parties and full economic and financial costs may be far greater than lost investment (see Box 3.2). In India, multiple projects have been delayed or suspended over a variety of reasons. For example, in 2016 the National Green Tribunal ruled to suspend the environmental license for the 780 MW Nyamjang Chu project, over concern for protected black-necked crane.[63] Project cancellations can occur for good reasons, but it is obviously preferable to find out about such reasons before major investment.

Beyond these high-profile examples, hydropower projects have been reported as having more delays and cost overruns than other large infrastructure projects.[66] From a sample of 61 hydropower dams with US$271.5 billion in construction costs constituting 114 GW of installed capacity, Sovacool, et al., found that hydroelectric projects experienced a mean cost escalation of 71 percent, representing a total of US$150 billion in cost overruns. Their analysis shows that cost overruns affected 75 percent of projects. Hydropower dams also had the longest mean construction time (118 months), largest total cost overrun (median of US$100 million per project) and time overrun (43 months) of all examined projects, including nuclear, wind, solar and thermal energy.[67]

Similarly, a study by the consulting firm EY found that the large majority of hydropower projects (80 percent) experienced cost overruns, an average overrun of 60 percent—with both proportions being the highest among infrastructure "megaprojects" (including coal, nuclear and gas power plants, offshore wind projects and water projects; Figure 3.4). Further, they found that 60 percent of hydropower projects experienced delays with an average delay of 2.5 years—among the highest for megaprojects.[68] While some in the hydropower sector have questioned whether these studies used sufficiently representative samples—

FIGURE 3.4

Among types of large energy and infrastructure projects, the proportion of projects with cost overruns and the average cost overrun.



and, no doubt, many hydropower projects are completed on time and within budget—there does appear to be a pattern in which hydropower projects tend to have more delays and cost overruns than other large projects, and environmental and social risks contribute to these tendencies.

From these studies, the extent to which environmental and social issues contributed to the delays and cost overruns is not clear. Hydropower projects are very site-specific with high upfront capital costs and a range of risks and uncertainties, including geotechnical problems, currency fluctuations, and contractual and labor issues. However, the fact that hydropower projects, particularly large ones, often create major impacts on communities and ecosystems—and sometimes get suspended over such impacts—does suggest that environmental and social issues are contributing to cost and schedule challenges. Better management of environmental and social issues could help hydropower from an investment perspective (lowering risk, increasing flows of investment) and not just from the perspective of meeting sustainability aspirations. Anecdotal evidence, statements from hydropower developers and financiers, and detailed reviews of projects (for example, published Protocol assessments and project

61 Ives, 2017.
62 Howard, 2014.
63 Koshy, 2016.
64 Braeckman and Guthrie, 2016.
65 Braeckman and Guthrie, 2016.
66 Ansar, et al., 2014; EY, 2016.
67 Sovacool, et al., 2014.
68 EY, 2016.

© MICHAEL YAMASHITA (IRRAWADDY RIVER SEEN FROM SHWE KYET YET PAGODA, SAGAING, MYANMAR)

BOX 3.2
Costs of Project Cancellations

Project delays and cost overruns receive an increasing amount of attention, but there is also another risk: total cancellation, or at least long-term suspension.

In some cases, that may be a good thing. After all, developers and governments should be selective. The environmental impact assessment may show unexpected impacts, an alternative energy source emerges as preferable, or the political risks increase because of a change in government. There are many good reasons to drop a project and a stage-gate process with rigorous evaluation of risks at each decision gate may help in avoiding high-risk projects.

However, in many cases this decision is made late, after considerable resources have been spent and, in some cases, construction has begun. In this chapter, we provide several high-profile examples from the past five years, including Myitsone (Myanmar), HidroAysén (Chile), and São Luiz do Tapajós (Brazil), representing an aggregate of approximately US$1.3 billion in stranded investment. At these advanced stages of project preparation or initiation, a number of banks, contractors, government agencies and other stakeholders have also invested significantly.

Sunk costs are but one way to look at the losses from cancelled projects. Another perspective is to consider the foregone revenue or profits. The expected financial net present value of the project, at the time of cancellation, may be a much larger loss. Also, there may be penalties for contractual breaches, as well as reputational damages. A track record of good project selection and management builds a reputation as smart investors, good risk managers and reliable business partners. It is difficult to demonstrate to the market that lessons have been learned from a cancellation, business practices have been changed and to demonstrate that a similar problem is unlikely to occur again. All of these issues may contribute to a significant loss of value for the project company.

Even that, however, is only part of the story. After all, the project was going to be built for a purpose: to deliver power and, possibly, other water and energy services. From an economic perspective, the reduced supply of power may increase power prices or, even worse, lead to black-outs. The cost of "unserved power"—the drop in economic output due to blackouts—is very high, much higher than the cost of almost all power supply options.[64] The projects described above, along with the 780 MW Nyamjang Chu project in India, represent nearly 18 GW of capacity that will need to be replaced by other projects. And, if the cancelled project was also supposed to provide flood control, irrigation or other secondary benefits, these also must be delivered in a different way, quite possibly at higher costs.

The reason a project was cancelled may of course be that it had unacceptably high negative externalities. In that case, the cancellation indeed had a net benefit for the economy. Surely, it would have been better if the project had been discarded earlier. It is quite possible that people and businesses already made decisions thinking that the project would go ahead: buying or selling land, or investing in other businesses (such as a shop, or a downstream irrigation system). The uncertainty of multiple delays and suspensions for those who were relocated, or are facing relocation, can lead to severe psycho-social anxiety in affected communities.[65] In the future, other local and foreign investors will look at the cancellation decision and demand a higher risk premium for investing in the country. In summary, there are many costs to pursuing the wrong projects, other than the funds already spent before they are cancelled.

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completion reports from development banks), support this link. In fact, a recent review of hydropower stated:

"The significant increase in hydropower capacity over the last 10 years is anticipated in many scenarios to continue in the near term (2020) and medium term (2030), *with various environmental and social concerns representing perhaps the largest challenges to continued deployment, if not carefully managed …*"[69]

Conclusions

A lack of strategic and system-scale planning and management for hydropower creates numerous risks—not just of greater environmental and social impacts but also conflict, delays and cancellations leading to investment risk and a risk to countries that hydropower investments will not achieve their potential to address national energy and water needs. For these reasons, the hydropower sector (regulators, developers and funders) should strive for improved processes for planning and management that can address shortcomings and maximize strategic values.

As discussed in Chapter 2, the estimated economic value of other water-management services in HIB ranges from US$285 to US$770 billion per year. Further, the basins provide sufficient fish protein to support at least 130 million people per year, fishing-based livelihoods for 50 million people and habitat for more than half of all fish species on earth.

These impressive numbers underpin a primary message of this report: *with hydropower development and management, the global scope of potential harm to other resources is dramatic, but so is the scope of potential benefit from better practices*.

Within "current development basins," river ecosystems and their services can be restored through dam removal, retrofits, reoperation (e.g., environmental flows) and coordinated operations of infrastructure. These interventions can often yield positive economic benefits for countries. Within basins where development lies mostly in the future, planners and stakeholders have the chance to "get it right the first time." There are far more degrees of freedom within these basins to plan, site and design projects and coordinate management—all within a framework that can reduce impacts and strive to produce broader benefits.

Underpinning these opportunities—and inspiring the need for collaborative solutions—is the reality that hydropower-influenced basins encompass nearly three-quarters of a trillion US dollars of other water-management values each year, more than half the fish species in the world and more than 80 percent of riverine fish harvests. Best practices in planning and management, for hydropower and other water-management infrastructure, have the potential to minimize impacts to those services and resources and deliver improved performance on those economic values. In the next chapter, we focus on the potential for system-scale planning and management—what we call Hydropower by Design—to promote these more-balanced and better-performing outcomes. We also demonstrate that pursuing Hydropower by Design makes business sense for investors and developers and can deliver broader economic benefits to countries and their citizens.

69 Kumar, et al., 2011; *emphasis added*

In Chapter 3, we reviewed a range of intertwined risks that confront hydropower development and management, spanning social, environmental, economic and financial dimensions. In this chapter, we explore how comprehensive and system-scale approaches to planning and management—what we call Hydropower by Design (HbD)—can help manage and reduce these risks and produce better outcomes across those dimensions.[70]

Recommendations for system-scale planning and management are not new. Many countries have conducted master planning for energy systems and river basin development, particularly during the 1950s to 1970s. In more recent decades, system-scale approaches based on concepts such as Integrated Water Resources Management and Integrated River Basin Management have been proposed to guide sustainable development.[71] However, successful implementation of these concepts has proven difficult (note, however, that there are examples and we highlight several in this report). Thus, we acknowledge the burden of proof required to differentiate the present recommendation for system-scale approaches and to describe how it can overcome constraints, address current needs and concerns and, in general, prove feasible.

The development and management of infrastructure and ecosystems within river basins is decidedly complicated. Due to this complexity, planning and management are often fractured into distinct institutions—each with their own information, modeling tools and objectives—that typically have little interaction - and that interaction tends to occur at moments that are more prone to conflict than constructive problem-solving.

CHAPTER 4 KEY POINTS

- Hydropower by Design focuses on integrating diverse groups and sectors—along with their objectives, data and models—at an early stage of management and planning decisions.
- Integration of the diverse modeling types used by different groups, within a system-scale framework, can more effectively identify potential common ground across groups and also reveal areas of increased financial value relative to project-by-project approaches.
- These financial benefits include system design optimization as well as improved risk management, reducing risk of delay and cost overruns.
- Through a quantitative case study of hydropower development decisions on the Magdalena River in Colombia, we show that these benefits can translate into superior internal rates of return (nine percentage points higher) for projects developed through a Hydropower by Design approach, compared to business as usual—and the projects are part of an overall system that has lower impacts and provides greater economic benefits to the country.
- In a set of 9 case study basins, HbD approaches increased the level of other economic values by 5 percent to more than 100 percent, compared to business-as-usual approaches, generally with no or limited reduction in energy generation, and, in some cases, a considerable increase in generation. These other economic values include water supply, flood-risk management, irrigation and habitat for migratory fish and biodiversity.

70 Appendices A and B go into much greater detail about the principles and processes of HbD.
71 WCD, 2000.

The challenges of bringing together these groups, along with their models and objectives, at a more constructive stage in the planning process arise from both technical constraints and perceptions. For example, different groups will use distinctly different modeling tools that do not easily "talk" to each other (see Table 4.1). The technical constraints of non-integrated planning approaches are exacerbated by perception. Strategic and system-scale planning has often been equated with time-consuming processes and delayed implementation. A government may be overly concerned that it will identify projects and options that are not financially attractive to developers and investors, inhibiting the flow of investment to meet development needs.

For countries to realize potential economic gains from system-scale approaches, investment needs to flow toward those strategic projects and management options. Thus, the projects and management options identified through Hydropower by Design must not only be strategic but also financially competitive. They may be financially superior outright, which will make them much easier to implement, or they may require subsidies or higher power rates to become attractive to investors.

In this chapter, we explore both the multiple benefits that can be achieved through HbD and how to integrate the models and information across different groups and institutions to demonstrate, at least at a proof-of-concept level, how model integration facilitates HbD. In the next section, we examine the models used by different groups involved with basin and energy planning and management, and explore how to integrate those models to identify development options that achieve broader economic goals while being financially competitive. Through an example from the Magdalena River, we show how the financial benefits of Hydropower by Design can, in effect, be used to "pay for" the more strategic outcomes that the process can identify.

In the second section, we explore a broader set of economic, environmental and social values that can benefit from Hydropower by Design, illustrating that HbD can generally result in economic improvement for one or more other important value or resource, often at little or no cost in terms of generation.

TABLE 4.1
Hydropower Functional Modeling Categories

Model Type/Objective Function	Typical User	Purpose
Water Management *Multi-Objective Simulation*	River basin authorities Academics NGOs	• Decision support tools for water allocation decision based on budgeting principles between inflows, consumptive uses, & non-consumptive uses • Can include environmental and social implications of water management • Traditionally not linked in integrated fashion to energy sector • Examples: WEAP, HYDRA, HBV
Capacity Expansion *Minimize Investment Cost or levelized cost of energy (LCOE)*	Energy planners State-owned utilities	• Explores buildout scenarios to optimize investment decisions among a set of available generation & transmission projects • Useful for examining impacts of power sector policies or alternative technology/fuel trajectories on generation & capacity • Examples: ReEDS, TIMES, OPTGEN, Plexos
Production Cost *Minimize Operational Cost*	ISOs (market operators) Utilities Project developers	• Uses pre-determined capacity mix to simulate decisions on economic unit commitment and dispatch among available power units such that operational cost is minimized. Time resolution of daily/hourly • Can be used to simulate future market system generation and pricing • Examples: EMPS, ProdRisk, Plexos, SDDP
Investment Return *Maximize IRR, NPV*	Project developers	• Optimizes developers' decision making on sequence of plants to be built and contracts to be signed • Examples: OptFolio, RETScreen

Integrating perspectives and models to capture financial and economic value

Hydropower by Design strives to overcome a fundamental challenge in the development, management and conservation of river basins and their resources: different groups—developers, government agencies and various stakeholder groups—have different objectives and use different criteria and models for making decisions (e.g., financial vs. economic, with more-or-less priority applied to diverse environmental and social resources). Particularly in regions undergoing new development, these differences are also reflected in different approaches to decision making, that vary with the group that—either by default or by design—plays a proactive role in setting the development direction. The approaches exert a strong influence on which projects are selected and how well they meet various expectations. For example, depending on the approach, project selection may result in projects that are financially competitive but may not meet broader strategic goals, or projects may be environmentally sustainable but not financially viable. How those determinations are made depends on who is leading the decision-making process:

1. *Developer-driven approach.* As many energy markets have been privatized and de-regulated, developers have been asked increasingly to propose projects to governments, sometimes in response to government bid requests. This leads to a predictable cherry-picking of easiest, least-cost projects, which may not deliver some broader economic benefits. Further, although developers may seek to avoid obvious environmental or social impacts, they often underestimate the risks associated with some impacts or may miss other impacts altogether due to inadequate scoping during the Environmental Impact Assessment phase. A project-driven approach also rarely accounts for system-level or cumulative impacts, resulting in projects that tend to miss opportunities and underestimate economic, social, environmental and financial risks.
2. A *public energy-planning approach* relies on government master plans and focuses on delivery of a range of energy services that the country will need (e.g., firm generation, peaking capacity, spinning reserve, black start capability, etc.)
3. A *multi-objective approach* relies on water-resource management models to address needs beyond the energy sector with analyses that identify economic costs and benefits that are relevant for various stakeholders. However, this approach generally does not consider financial cost and revenue perspectives and so is also susceptible to identifying financially unviable options. In some cases, the government can afford to finance preferred strategic options, but, in cases where external investment is needed, a disconnect between strategic systems and financially viable projects can inhibit the flow of investment.

Although these different planning approaches will generally lead to the identification of different sets of projects to meet the varying objectives, there is likely more common ground than these differences would suggest. In other words, although different institutions are optimizing based on different criteria (financial, economic, environmental and social), constructive engagement at early stages has the potential to identify options that will produce more overlap in terms of benefits with fewer conflicts.

The pursuit of this constructive engagement is made more difficult by the fact that the groups tend to use different models. The development and management of hydropower implicates energy, water resources management and conservation of environmental and social resources. Due to this complexity, it is not surprising that different groups have developed specific modeling methodologies to help optimize for their respective interests. These models can be organized into the following four functional categories (Table 4.1 provides further detail):

1. Water-Resource Management models, which offer tradeoff comparisons between different water users and are typically used by river basin authorities, academics and NGOs;
2. Capacity Expansion models, which are traditionally the purview of government planners and regulators, are designed to find least-cost solutions for reaching energy targets;
3. Production Cost models, which create the weekly, daily and hourly dispatch rule sets and are most relevant to market operators and developers; and
4. Investment Return models, which define project rate of return characteristics for developers and investors.

These models feature a diverse array of objective functions, meaning that a problem's optimal solution differs from model to model. This is important, as the objective function represents a proxy for the interest of the model user and, to the extent that these models do not talk to one another, these differences in models and objective functions serve as barriers to effective communication and collaboration across groups.

Each of the decision-making approaches described above (developer-driven, etc.) relies on models from a distinct functional modeling category (Figure 4.1a), illustrating the technical challenge that exacerbates the inherent differences in objectives. A key principle of HbD is that early integration of objectives, data and models will increase the likelihood of finding outcomes that satisfy a range of stakeholders' interests (Appendix A). Within that general theme of integration, early model integration will allow stakeholders and decision makers to have a common foundation of analysis, delivering results to each group that provide meaningful information and a basis for evaluation. Though some basic differences in objectives inevitably persist, this common foundation provides a much more effective platform for constructive dialogue and an improved opportunity to identify projects that can meet a range of expectations: financially competitive, economically strategic and lower impact on environmental and social resources (Figure 4.1b).

Importantly, the integrative approach inherent to HbD, including model integration, can yield insights that would not emerge through isolated perspectives. These insights contribute to the potential for finding balanced outcomes and are key to both the economic and financial business cases explored in this report. In the next section, we show how HbD can provide financial value to developers and investors and explore how model integration can identify strategic, low-impact systems composed of financially competitive projects.

Financial value revealed through integrated approaches

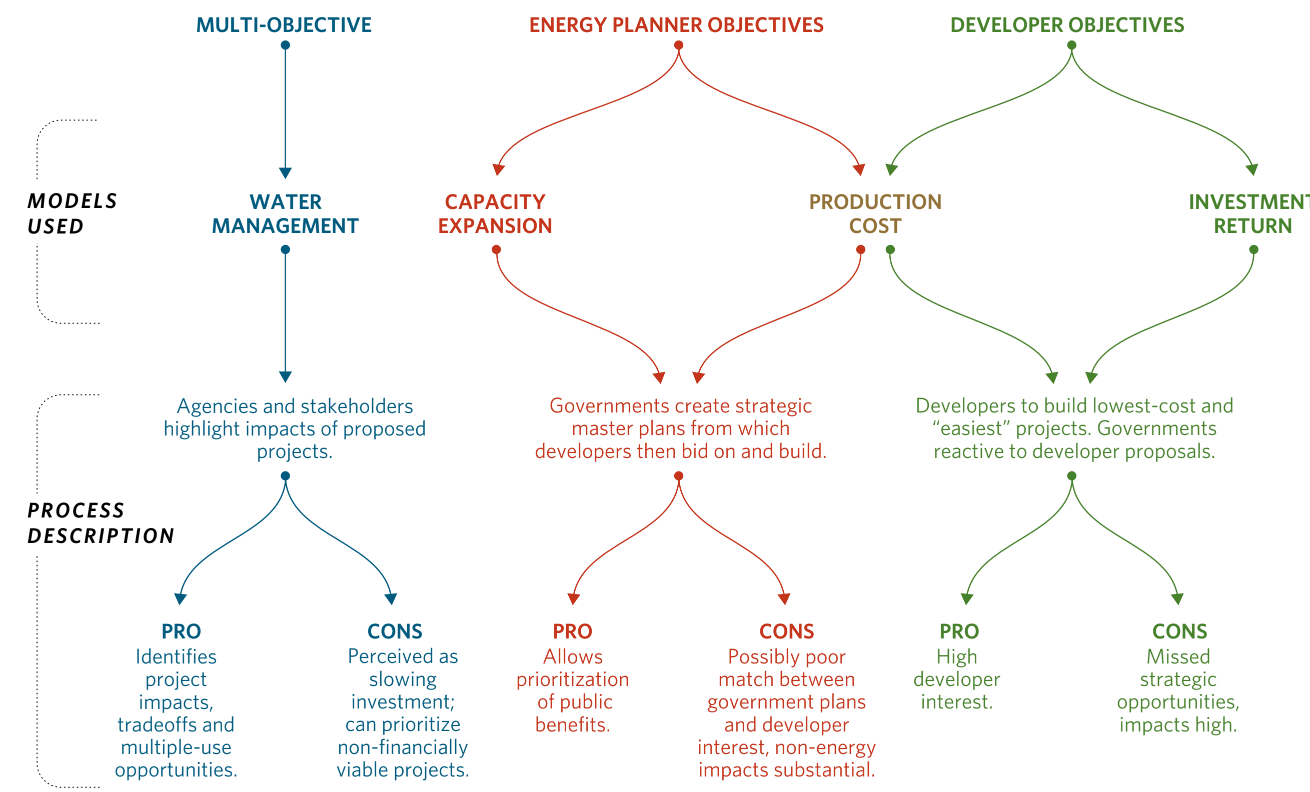
Hydropower by Design's integration of perspectives and models (Figure 4.1b) makes it is possible to capture two key sources of financial value: one, system design optimization and, two, improved risk management to reduce delays and cost overruns due to environmental and social impacts.

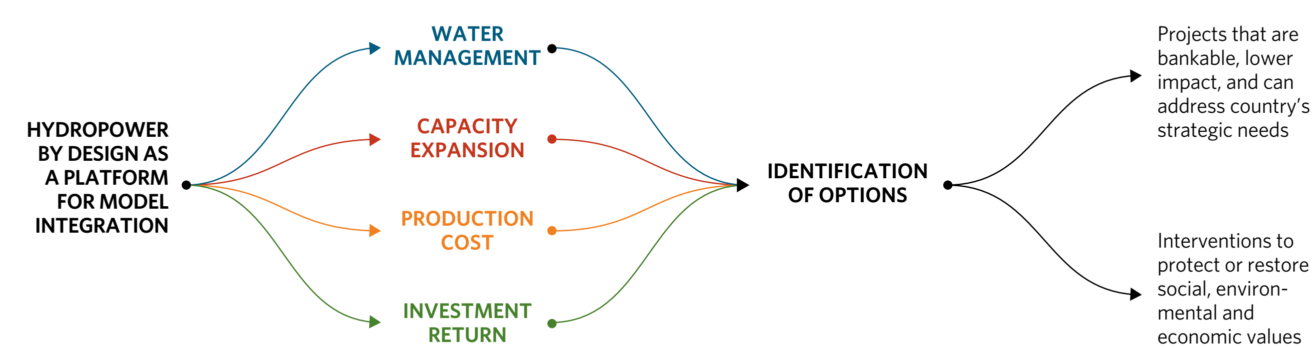
Benefits derived from system design optimization

The first financial benefit generated by HbD arises from approaching investment decisions in a basin as a long-term financial optimization problem, as opposed to the developer-driven model which looks at investment decisions through single-project criteria and can emphasize relatively short-term financial targets (i.e., Business as Usual or BaU). This may result in developers cherry-picking the easiest and lowest-cost projects, but not necessarily those that will work together most effectively as a system. The single project approach misses opportunities to capitalize on system-scale financial value, because each individual project, built to meet expectations of a single developer, changes the physical context in the basin for all future development opportunities. This is perhaps most obvious in terms of changing flows, the fuel for downstream power stations, but also applies to catchment management, sediment, dam safety, access roads, transmission lines, available land for displaced communities, fish passage and many other issues where single-project decisions can result in the cascading effects of performance and financial inefficiency. An integrated approach to modeling, which embeds decisions about individual projects within a system-optimization approach, can identify a set of projects that capture system-level financial efficiencies. This results in a portfolio of individual projects with greater average financial performance than the BaU approach.

FIGURE 4.1

(a) Different groups and how they use four functional modeling categories that provide information relevant to HbD. Note that here, "water-management" models can integrate many environmental and social issues as sub-models or linked models; (b) a conceptual illustration of how HbD can provide a platform for integrating these functional modeling categories.





Benefits derived from social and environmental risk reduction

The second source of financial value results from improved risk management which can inform site selection and design and contribute to reduced cost and time delays associated with environmental and social impacts. Delays can cause significant reductions in projects' internal rate of return (IRR), as each month a project is delayed results in a month of additional expenditures and foregone revenues. As discussed previously, hydropower has among the highest rates and levels of both time delays and cost overruns. Though there are numerous sources of risk that contribute to delays and overruns, social and environmental issues (described in Chapter 3 and Appendix C) are relatively common and have contributed to some of the most high-profile delays, overruns and cancellations. Hydropower by Design strives to identify development options that minimize those impacts. By bringing water resource management and ecosystem models into the selection and design process for new projects, project risks can be assessed more realistically and risk projections can be incorporated into investment return models. This results in a portfolio of projects with a lower percentage that will encounter significant delays and cost overruns due to environmental and social risks, improving the distribution of projects' IRR compared to the BaU approach.

In countries with strong regulatory structures, environmental and social risks are usually identified during the licensing process and stakeholders' disagreements can translate into significant regulatory delays. In a strong regulatory environment, application of the principles of HbD can lower regulatory uncertainty and potentially result in streamlined review and licensing, reducing the time and cost of that step in the development process (see Box 4.1).

These sources of value can produce incremental financial benefits which could be shared among various parties. While investors could achieve greater returns—and, indeed, ensuring that systems are composed of financially attractive projects is one of the benefits of this integrative approach—government decision makers could also decide to put this incremental financial value to use, in effect using it to "pay for" more strategic outcomes. Financial benefits could be channeled back to society in various forms, including lower energy tariffs, incorporation of strategic multipurpose functions into hydropower dams, or alternative siting to avoid social and environmental impacts.

Improved Internal Rate of Return through Hydropower by Design

To explore these sources of financial value, we examined multiple buildout scenarios for the Magdalena River basin in Colombia, using a combination of water-management, investment return and production cost models (see full case study in Chapter 5). The buildout scenarios applied different decision criteria to select projects to meet a generation target, including:

1. *Business as usual* – designed to mimic a "cherry picking" approach, projects were selected in a sequence determined by the Net Present Value of each individual project.
2. *System optimization* – projects were selected based on financial criteria that considered system-scale efficiencies, optimizing site selection and project sequencing based on the Net Present Value for the long-run of the overall basin.
3. *System optimization and risk management* – projects were selected using the system optimization, as above, and improved consideration of environmental and social risks, intended to reduce the likelihood of associated delays and cost overruns.
4. *Hydropower by Design* – projects were selected using system optimization and improved consideration of risks and also included criteria intended to achieve high performance for specific conservation goals (e.g., maintain connected river systems for migratory fish).

We found that the scenario that incorporated system optimization and risk management identified a portfolio of projects with improved average Internal Rate of Return (IRR) compared to the BaU (Figure 4.2). Through the BAU approach, each project "locks in" a location and flow regime that is advantageous to the project, but a sequence of these decisions collectively falls short of the financial potential of the basin.

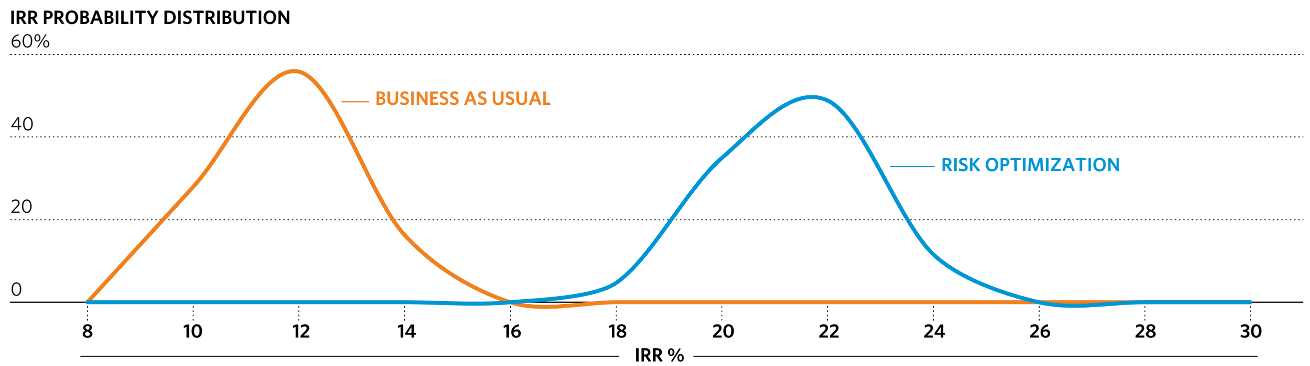
This financial benefit could be used to "pay for" the strategic outcomes pursued in the Hydropower by Design scenarios.

BOX 4.1
Streamlined Regulatory Review for Renewable Energy

Although focused on a different generation source, an example from solar development in the southwestern US provides some general insights into the benefits of system-scale planning for streamlining regulatory review for renewable energy. In 2009, the American Recovery and Reinvestment Act catalyzed a boom in utility-scale solar energy development on public lands in the Mojave Desert. Despite the popular image of a wasteland, these areas are incredibly rich in biodiversity (e.g., rare plants, desert tortoise, bighorn sheep, etc.). The rush of projects was uncoordinated, often overwhelming the agencies tasked with processing them and creating many conflicts that led to litigation from environmental groups. In response to this dynamic, the US Department of Interior undertook an unprecedented landscape-scale, conservation- and development-planning approach to identify upfront low-conflict zones for utility scale solar energy development across six southwestern states (Nevada, California, Arizona, Utah, Colorado and New Mexico). The 2012 plan, called the Solar Programmatic Environmental Impact Statement (Solar PEIS), established 17 Solar Energy Zones across the six states where development would be focused and expedited. The success of the approach was demonstrated first in the Dry Lake Solar Energy Zone (SEZ) on public lands near the city of Las Vegas. In June 2014, the US Bureau of Land Management held a successful auction to lease the 23 square kilometer site for solar development. In June 2015, the three projects inside the Dry Lake SEZ were permitted by the BLM. While the average licensing time for a solar project is 21 months, the licensing times inside the Dry Lake SEZ were cut to 10 months. In addition, the mitigation requirements for the projects were determined in advance of the licensing, creating certainty for both the developers and conservation projects. The economic benefit of the approach is reflected by the fact that the first project to be built at the site, a 100MW solar project by First Solar, set a national record for the lowest cost solar energy in the country.[72] Overall, the success of the Dry Lake Solar Energy Zone—from economic, regulatory and environmental perspectives—stands as testimony to the value of a comprehensive and system-scale approach to infrastructure siting and licensing.

FIGURE 4.2.

IRR Probability Distribution across potential hydropower projects in the Magdalena Basin, compared between Business as Usual and Risk Optimization scenarios.



72 Kraemer, 2015.

Applying Hydropower by Design to promote sustainable outcomes and economic benefits

Hydropower by Design can be applied across the full lifecycle of infrastructure: from planning the expansion of hydropower dams in a river basin or region, to the reoperation of individual dams or cascades, to the strategic removal of dams that have outlived their intended purposes. Applications of HbD will vary by the level of development in a basin and the range of other resource objectives and constraints imposed by other sectors. Here, we explore the application of HbD in the four types of basins described in Chapter 2. Note that these categorizations are primarily illustrative: river basins, infrastructure systems, ecosystems and energy systems are all quite complex and so the actual constraints, opportunities and relevant interventions will vary greatly within the four broad categories. However, there are likely to be certain interventions that will tend to be more relevant in certain basin types and we feature those here.

In the case studies, we modeled application of HbD approaches[73] to planning and/or management challenges and found that the levels of environmental values and the economic values of other water-management services could be increased by 5 percent to more than 100 percent, generally with no or limited reduction in energy generation and, in some cases, a considerable increase in generation (Figure 4.3). These improvements are highly basin-specific due to the complicated nature of interacting economic, social, infrastructure and biophysical systems. Within the case studies, options could often produce improvements for multiple values but the cases also illustrate that tradeoffs emerge in scenarios where improvements in two or three values come at the cost of a reduction in another. Such tradeoffs are common in water management—and economic development in general. While Hydropower by Design cannot escape this reality, it can help make those tradeoffs quantified or otherwise clear to stakeholders and decision makers.

The applications of Hydropower by Design varied across the types of river basins and with the important services and resources within individual basins. In each case, a HbD scenario was compared to a BaU scenario with comparable financial cost and/or comparable economic cost, except where noted.[74] Full case studies are found in Chapter 5.

Future development, water abundant.

- In river basins with primarily single-purpose hydropower dams, the case studies focused on hydropower generation and migratory fish habitat. We found that the extent of connected habitat for migratory fish could be increased by 20 to 300 percent, often for similar levels of generation and investment (Kouilou-Niari, Amazon, Irrawaddy and Mekong basins.)[75]
- With the Yangtze case study, we focused on a reallocation of reservoir storage within a proposed cascade of hydropower dams. By reducing the flood storage allocation we found that hydropower generation and revenue could be increased by 10 percent. Investing a portion of that increased revenue in reducing flood risk in the floodplain downstream would result in an overall reduction in flood risk. This change in reservoir storage and operations also improved the flow regime for a Native Fish Reserve. This case illustrates that the system approach of Hydropower by Design, and the search for options that perform well across multiple objective, can be expanded to include management of floodplains.

Current development, water abundant.

- The Penobscot case study, based on an implemented project, illustrates the potential for strategic removal of old hydropower dams. Two dams were removed and a third dam was bypassed with a nature-like fish passage, resulting in a 450 percent increase in the length of river and stream channels accessible to migratory fish. In two years since dam removal, several species have responded with dramatic increases. River herring populations, for instance, are 135 times greater after dam removal than before (Figure 4.4). Due to operational and equipment changes at remaining dams, the hydropower system in the basin after dam removal will produce slightly higher generation than it did before.
- The Savannah River case also considered a reallocation of flood storage (similar to the Yangtze above). We found that a partial reduction in flood storage, coupled with downstream mitigation actions, could result in a 10 percent increase in hydropower and improved water supply and environmental flows.

73 One case study, the Penobscot, describes the results of an implemented project that balanced river restoration and energy generation.
74 Business as Usual cases were defined based on: one, actual management decisions; two, government plans; and, three, modeled as a set of decisions focused on maximizing performance for individual projects, but not an overall system. Chapter 5 provides more details on the case studies.
75 Note that the Mekong, Irrawaddy and Amazon are not shown in Figure 4.3 because those case studies did not include financial or economic analyses.

FIGURE 4.3

Economic and environmental improvement possible through application of Hydropower by Design in modeled case studies from nine river basins. In each case, a Hydropower by Design scenario was compared to a Business as Usual scenario with comparable financial cost and/or comparable economic cost.

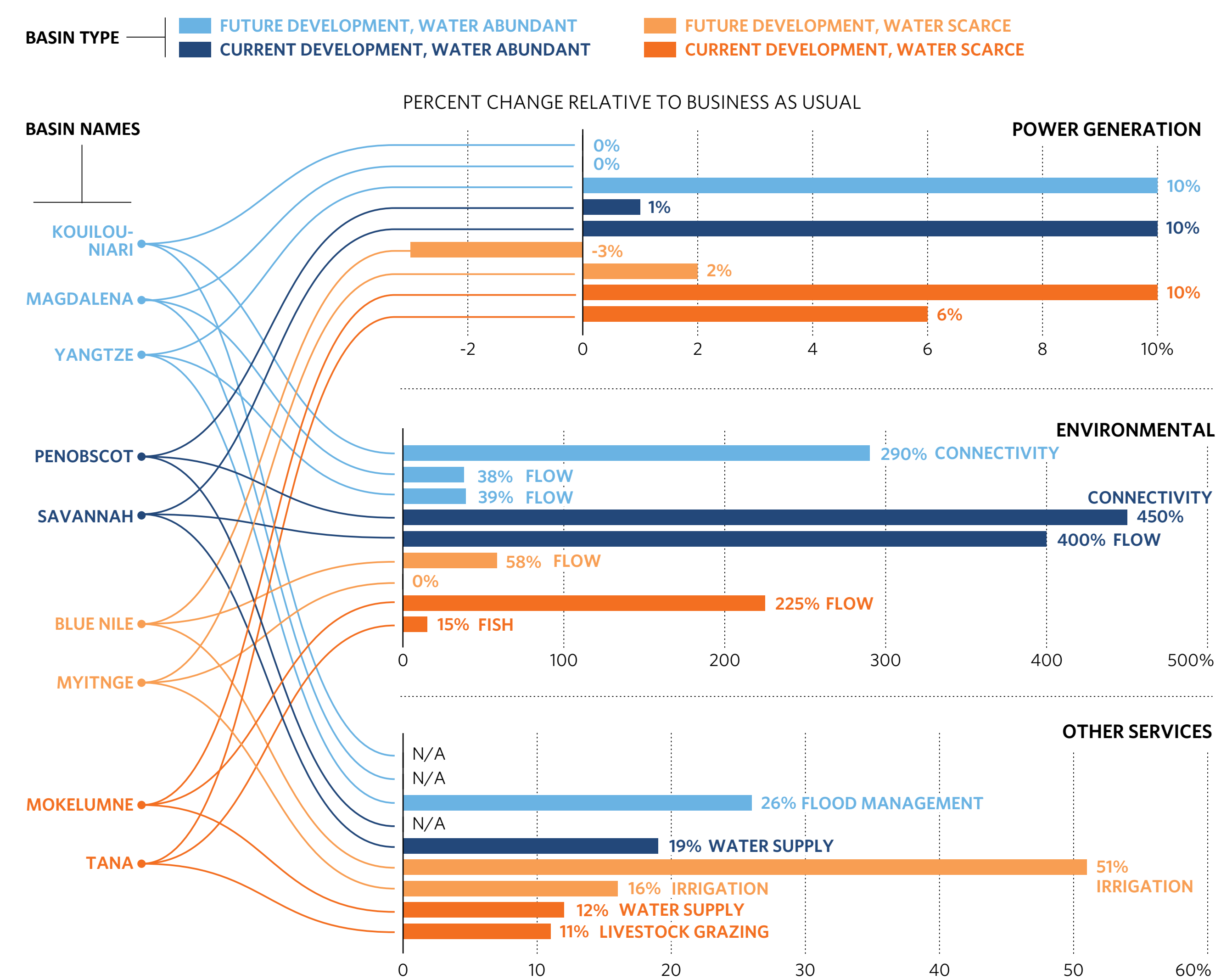


FIGURE 4.4

The removal of Veazie Dam on the Penobscot (top) and river herring spawning in Blackman Stream, a tributary to the Penobscot now accessible to migratory fish after dam removal (bottom).

TOP: © JOSH ROYTE/TNC; BOTTOM: © SEAN FITZPATRICK/TNC

Future development, water scarce.

- In two basins, the Blue Nile and Myitnge, the Hydropower by Design approach offered a better balance between hydropower generation and irrigation, with improvements related to irrigation of 15 to 50 percent for comparable generation. In the Blue Nile, the HbD approach offered considerable improvement in environmental flows (a 60 percent reduction in flow alteration). In the Myitnge, however, the environmental performance (measured in terms of potential fish productivity) did not differ between HbD and BaU (i.e., there was no improvement in environmental performance possible while providing similar energy generation).

Current development, water scarce.

- The Mokelumne is a third case study that considered reallocation of flood storage coupled with downstream floodplain management. In this case, hydropower was increased by 10 percent and both water supply and the ability to release environmental flows were also improved.
- With the Tana River, there was little room for improvement under the rules set by the existing Power Purchase Agreements. Relaxing those agreements allowed for a 6 percent increase in generation along with improved performance of floodplain resources, including fisheries (15 percent) and floodplain grazing (11 percent).

Summary of economic improvement

In Chapter 3, we estimated that the economic value of other water-management services within hydropower-influenced basins (HIB) was considerable—between US$285 and US$770 billion per year—and these basins also encompass the majority of the world's freshwater fish species and riverine fish harvest. All of these economic values and resources can be negatively impacted by hydropower development and operation, but through a set of interventions described in this chapter, the application of system-scale approaches to planning, siting, operation and even strategic removal can result in lower impacts or even restoration of environmental resources and improved economic performance. The case studies showed potential improvement ranging from 5 percent to more than 100 percent for various water-management services and environmental resources.

River basins are inherently complex with extremely site-specific combinations of resources, constraints and opportunities. For example, while performance for some resources may be positively correlated in one basin, they may be negatively correlated in another. Thus, extrapolating from a set of case studies to a global perspective is quite difficult and we will not try to make specific, geographically based predictions or quantifications of global economic gains that would be possible through widespread application of Hydropower by Design.

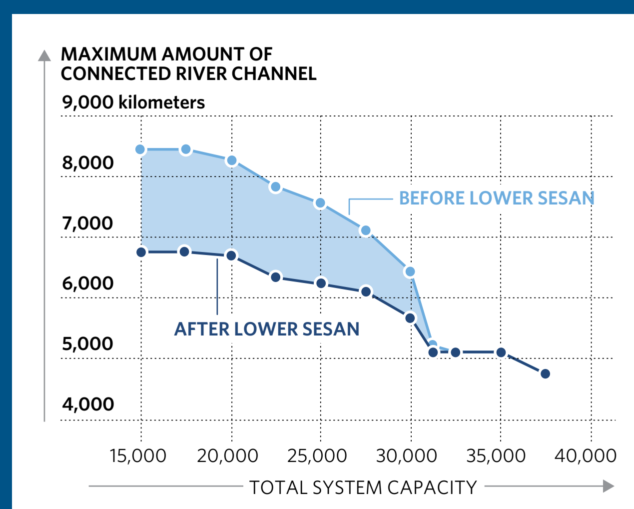
However, it is instructive to consider the potential global scope of improved economic performance that could arise from widespread use of Hydropower by Design. For example, if system-scale approaches to hydropower planning and management could achieve a net improvement of even 5 percent in other-water management services, that would result in increased global economic value of US$14 to US$38 billion per year—a number that is comparable to average annual investment in hydropower. This underscores that countries and development organizations should be motivated to promote the planning, decision-making, financing and regulatory processes necessary to secure these potential gains (see Chapter 6 for discussion of mechanisms to promote uptake of HbD). The realization that far greater than 5 percent improvement may be possible in many areas should further motivate implementation. In general, HbD can offer greater potential for improved performance across a wider range of resources if it is implemented earlier in the planning process (Box 4.2).

BOX 4.2
Benefits of early implementation of HbD

The importance of implementing HbD as early as possible in the development process is clearly illustrated by hydropower in the Mekong basin. In a case study in Chapter 5, we discuss tradeoffs between hydropower and migratory fish habitat at the basin scale, namely the extent of the channel network connected to the lower river system. That case study describes a dam, Lower Sesan 2, proposed for a tributary of the Mekong (the Sesan River) which was identified as having disproportionately high impacts on river connectivity[76]—yet was approved for development the year after that study was published. Here, we examine how the decision to build that one dam affects future options for maintaining migratory fish habitat in the Mekong. Figure 4.5 shows projections for the maximum connected river habitat available, at various levels of total hydropower development, with Lower Sesan 2 already developed (as is now reality), or if Lower Sesan 2 remained a potential dam site. A system planning exercise conducted before Lower Sesan 2 was built could have identified many more options for balancing energy and fish habitat. Planning begun after that dam was developed is now constrained and the best options for balancing energy and fish habitat have lower performance. This illustrates the more general point that influencing site selection provides more degrees of freedom for optimization and a better opportunity to find balanced solutions. Implementing system approaches after site selection has happened can still influence design and operation, but is more constrained in terms of potential options.

FIGURE 4.5

Options for balancing hydropower capacity and migratory fish habitat while Lower Sesan was a potential dam ("before Lower Sesan"; blue) and after it was developed ("after Lower Sesan"; red). The points represent the maximum amount of connected river channel that is possible at that level of capacity development. Note that kilometers include mainstem rivers and connected tributaries with a mean annual flow greater than 10 cubic meters per second.



Conclusions

This chapter has summarized the potential economic and financial benefits of Hydropower by Design, including that it can identify infrastructure options that are: one, lower impact and more strategic; and, two, financially competitive.

In short, the business case for HbD is that it can offer countries a better deal: system-scale approaches to planning and management can deliver broader development benefits, with greater social and environmental sustainability. By capturing various sources of financial value, these better outcomes can be consistent with the needs of developers and funders, where infrastructure development depends on private investment. Because a warming climate and changing precipitation patterns will likely increase uncertainty and risk across multiple dimensions—including hydrological, environmental and financial—and also increase competition for water, climate change strengthens the business case for countries, developers and funders to pursue comprehensive and system-scale approaches to planning and management of hydropower, embedded within both energy and water-management systems (Appendix D).

The trajectory of recent hydropower development in Chile illustrates several key points (see Box 4.3): a single project focus in site selection led to high-profile conflict and, ultimately, financial losses and uncertainty for developers and investors. The country also paid a price in terms of delivery of needed energy. The result has been a move toward integrated system planning, including combining hydropower with other renewables.

While this chapter has emphasized that improved performance across multiple resources can be possible through Hydropower by Design, we note three caveats. First, for future development, we compare a Hydropower by Design development scenario with a Business as Usual development scenario, not with current conditions. Thus, improved performance for a value such as fisheries means Hydropower by Design may offer better outcomes than status quo development, but still may represent a decline in fisheries from current, low development levels (the examples from the Mekong, Irrawaddy and Amazon all illustrate this as the comparisons are between more and less loss of migratory fish habitat).

An additional caveat concerns storage. Multipurpose reservoirs include water storage and many of the multiple benefits for water and energy management discussed above commonly require storage. However, we are not promoting a general recommendation to increase storage, because storage is also associated with increasing many of the negative impacts discussed in Chapter 3. Rather, we are suggesting that "storage by design" can be a key part of Hydropower by Design, following the same basic principles (see Box 4.4). Planning processes should strive to understand realistic needs for energy and water management and environmental and social resources and understand the tradeoffs associated with using storage to meet those needs. If a country will seek to build storage for other purposes (e.g., irrigation or grid stability) then those needs should be fully considered when planning and developing hydropower (e.g., hydropower planning should not focus just on adding an increment of generation, but consider how different infrastructure investments can meet strategic needs and what are the impacts of those options). Without integrated planning, a high-value storage site may be developed as a run-of-river hydropower project, because the smaller project was easier to fund and quicker to build. However, if the country still needs storage, then it will need to build at a less-desirable site and then two dams are built whereas with integrated planning perhaps one would have sufficed. In this framework, assessment of storage is not just limited to new traditional reservoirs, but should also include other forms of storage, such as pumped storage or coordinated operations within an existing cascade.

Third, improved performance of multiple resources is strongly case-specific and can't be generalized. In other cases, those resources may be negatively correlated. Some resource objectives are commonly incompatible (e.g., storing water for irrigation and maintaining high flows to inundate floodplain wetlands may be hard to reconcile). Tradeoffs are inherent in policy and management decisions and, at times, those tradeoffs can be extremely unappealing. Even careful application of an approach like Hydropower by Design cannot guarantee that all resources and services will benefit. One of the primary values of Hydropower by Design, or system planning approaches in general, is its ability to make those tradeoffs clear to inform decisions.

76 Ziv, et al., 2012.

BOX 4.3
Restoring Public Planning Capacity in Chile

For decades, Chile relied on the private sector to select and build power projects, without much consideration for environmental and social concerns. But this model became increasingly untenable. In 2014, Chile's incoming government cancelled the largest energy project in the history of the country, the five-dam, 2,750 MW HidroAysén project in Patagonia, after intensive conflict, including mass demonstrations in Santiago. This was the culmination of years of disagreements over new hydropower, thermal and transmission projects. Projects were stopped by community and civil society opposition, the environmental licensing agency, the Supreme Court and in the case of HidroAysén, by the cabinet. The lack of investments in new capacity contributed to a surge in power prices, which rose by an average of 11 percent per year between 2000 and 2013. This in turn threatened the competitiveness of industries, for example copper mining, which consumes about a third of Chile's power.[77]

The new government recognized that selection of projects by developers, at least in the hydropower sector, had to be guided by government in some way. It will take some time, however, to build an information base, capacity in government and a new model for joint public-private responsibility in planning. An initial step was to increase transparency by creating a public platform on sustainable hydropower, which includes detailed information on environmental, social, cultural and economic values in all river basins.[78]

The urgency has been reduced, for the time being, by slower growth in power demand and a boom in wind and solar power. Chile's 2016 power auction resulted in the lowest-ever bid for solar PV globally, at US$29.10 per MWh.[79] However, at some stage the increasing market penetration by solar and wind will require more flexible back-up capacity. One project under consideration is on the northern desert coast. It is a combined 600 MW solar and 300 MW pumped-storage facility. The pumped storage component would use the Pacific Ocean as its lower reservoir and a natural concavity on a 600-meter-high cliff as its upper reservoir.[80] Even if the pressure on conventional hydropower development is reduced for now, the Chilean government will want to ensure that through more proactive and comprehensive planning, it can avoid a repeat of the recent supply crisis.

However, difficult tradeoffs can potentially be reduced or resolved by moving to larger scales, such as moving from a river basin to a region or a whole country. For example, the planning systems from Norway and Iceland looked for balance between basins more so than within them, as in identifying specific river basins more appropriate for protection and others more appropriate for being developed by energy (note that this is not a strict division; even within basins designated for development, system-planning can still seek more-balanced outcomes through careful siting and coordinated management). This is a further extension of the same logic that moving from the project scale to the basin scale can reduce zero-sum tradeoffs and open up a broader range of potential solutions for finding balance. This is why we refer to Hydropower by Design as being "system scale," because the scale of the system that offers the best solutions can vary, from a cascade, to a river basin, to a grid or country—even a region composed of several countries.

This logic of searching for the right scale of system extends beyond geography to encompass other sources of energy. Broadening the search for balanced solutions beyond hydropower to include other sources of generation can alleviate difficult tradeoffs, such as particularly unacceptable impacts. The case study on Sarawak (see Chapter 5) illustrates how increasing reliance on other low-carbon sources of generation could allow the region to meet energy needs without problematic and contentious impacts on forests and indigenous communities. Though comprehensive assessment of other generation sources was beyond the scope of this report, the Sarawak case study and the example from Chile in Box 4.3 both point to the potential benefits of this integrated approach to energy planning. This integrated approach allows the possibility of identifying development options that simultaneously work for energy systems, social and environmental systems and the world's climate system.

77 Gordon, 2013.
78 Minister of Energy – Government of Chile.
79 Elena, 2017.
80 International Water Power and Dam Construction, 2016.

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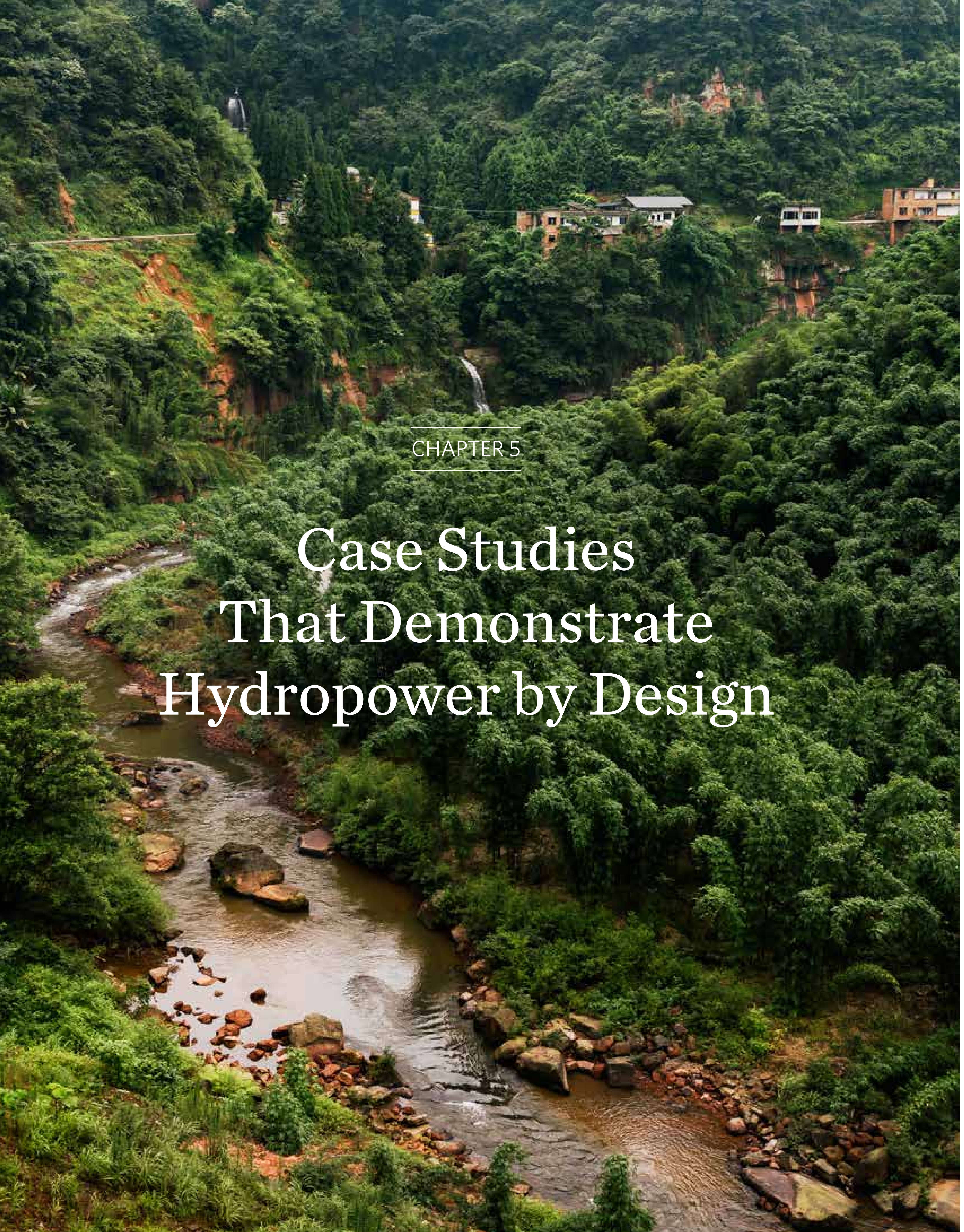
BOX 4.4
"Storage by Design"

Storage can be beneficial for water and energy systems. It reduces the variability of river flows for various purposes (such as irrigation and flood control) and it increases the load factor for baseload hydropower plants and the reliability of power supply, particularly if the share of variable renewables in the generation mix is increasing. If river flows become more variable with climate change, as expected, the case for storage becomes stronger (see Appendix D). Storage also comes with downsides, however. Many of the negative impacts reviewed in Chapter 3 are higher with storage dams, including displacement of people, flow alteration and sediment capture. Further, storage dams are complex to operate if serving multiple purposes at once and are generally more expensive. Developers are often reluctant to take on storage projects, preferring simpler run-of-river projects.

A "storage by design" approach would be based on a broader options assessment for energy and water to determine which water and energy needs require storage in reservoirs and which can be meet through non-dam alternatives and which through reservoirs.[81] Based on that guidance on reservoir storage needs, the approaches discussed in this report would then be applied to assess how different infrastructure options (site, design and operation) can meet those needs and what the tradeoffs are. This approach can identify options that go beyond simply adding more storage when the need arises. Improved system planning can reduce the need for storage, for example by combining complementary sources of power in a grid. Where new storage is needed, this approach can identify options to site it in places where it has the least possible negative and the highest possible positive impacts. The SHARE concept for multipurpose hydropower dams provides a useful framework for considering how storage can be planned and operated to meet multiple purposes, with the "R" of SHARE emphasizing the importance of a river basin perspective.[82]

81 WCD, 2000.
82 Branche, 2015.



CHAPTER 5

Case Studies That Demonstrate Hydropower by Design

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The discussion of economic and financial benefits of Hydropower by Design in Chapter 4 was drawn from literature review and a set of nine case studies. Those case studies are examined in greater detail in this chapter. The Amazon, Irrawaddy and Mekong rivers are covered in a single case study as they share a common approach and common focus on migratory fish habitat; the Kouilou-Niari basin is also discussed in that section as it too focused on migratory fish habitat.

The cases are presented in this chapter in the order of the four types of basins in the table below (Table 5.1), with the exception of the Yangtze, Savannah and Mokelumne. Although these three basins span three different basin categories, they share a similar conceptual approach that integrates floodplain management as part of the assessment of options and tradeoffs.

TABLE 5.1

The case study basins. Figure 4.3 summarizes results from the basins with economic or financial analysis.

Type of Basin	Case Study	Geography	Resources Considered	Economic or Financial Analysis
Future Development, Water Abundant	Amazon	South America	Hydropower and migratory fish habitat	No
	Irrawaddy	Myanmar	Hydropower and migratory fish habitat	No
	Kouilou-Niari	Republic of Congo	Hydropower, migratory fish habitat, biodiversity, land use (transmission lines)	Yes
	Magdalena	Colombia	Hydropower, biodiversity, land use	Yes
	Mekong	Southeast Asia	Hydropower and migratory fish habitat	No
	Sarawak *Includes Baran River Basin*	Malaysian Borneo	Hydropower, land use (forests), indigenous land, emissions	Yes
	Yangtze	China	Hydropower, flood-risk management, river connectivity, environmental flows	Yes
Future Development, Water Scarce	Blue Nile *Tributary to Nile*	Ethiopia	Hydropower, environmental flows, irrigation	Yes
	Myitnge[83] *Tributary to Irrawaddy*	Myanmar	Hydropower, fisheries, navigation, irrigation	Yes
	Penobscot	Maine, USA	Hydropower and migratory fish habitat	Yes
Current Development, Water Abundant	Savannah	Georgia and South Carolina, USA	Hydropower, flood-risk management, water supply, recreation, environmental flows	Yes
Current Development, Water Scarce	Mokelumne	California, USA	Hydropower, flood-risk management, water supply, environmental flows	Yes
	Tana	Kenya	Hydropower, floodplain productivity (fisheries and grazing)	Yes

83 The Myitnge is a tributary of the Irrawaddy. Based our hydrological criteria, the Irrawaddy is classified as water abundant. However, the Myitnge flows into the Irrawaddy in the middle of Myanmar's dry zone, a relatively arid part of the country in which irrigation is important. Because of those conditions, we placed the Myitnge within the category of water scarce basins.

Amazon, Irrawaddy, and Mekong River Basins

The Amazon, Irrawaddy and Mekong river basins share at least three major characteristics. All three: one, support among the largest riverine fish harvests in the world with migratory fish composing an important component of harvest; two, have high levels of richness of fish and other freshwater species; and, three, are among the river basins with the most proposed hydropower dams. Completion of planned dams would more than double total capacity in the Mekong, roughly triple capacity in the Amazon and increase capacity by more than five times in the Irrawaddy. Buildout at this scale would dramatically increase the fragmentation of river networks in those basins.[84]

Migratory fish, however—particularly those that make long-distance migrations—require unfragmented channel networks to move between various parts of the river basin. For example, in these three tropical basins, many migratory fish move between downstream habitats of the system (the lower main channel and its floodplains and delta) to spawn in upstream habitats, including tributaries. Fragmentation of these migratory corridors can result in dramatic losses of migratory fish biomass, as happened with salmon in temperate rivers, such as the Rhine and Columbia, and is projected to occur on the Mekong with construction of mainstem dams (Figure 5.1). A strategic environmental assessment for mainstem Mekong hydropower reported that completion of all mainstem dams could reduce migratory fish biomass by up to 42 percent (Figure 5.2).[85] A study that only considered tributary dams found that fragmentation from those dams alone could cause migratory fish biomass to decline by nearly 20 percent.[86] In addition to impacting fish harvest, fragmentation from dams is a leading cause of the decline and loss of fish and other freshwater species.[87]

A large decline in migratory fish biomass would have a significant impact on people who depend on wild capture fisheries for food and livelihood. In the lower Mekong, capture fish harvests are approximately 2.3 million tons per year (nearly 20 percent of global freshwater fish harvest) with an estimated economic value of US$11.2 billion. Orr, et al., found that this source of protein would be difficult to replace for countries such as Laos and Cambodia.[88] Further, for low-income rural people, wild capture fish provide a source of protein that does not require currency and can be sold to generate cash income. Loss of this source of food and livelihood would certainly cause significant short- to medium-term disruptions for fishing-dependent communities.

AMAZON
Area (km²): 6,009,241
Mean Annual Flow (cms): 205,000
Population: 33,000,000

IRRAWADDY
Area (km²): 377,193
Mean Annual Flow (cms): 13,000
Population: 29,000,000

MEKONG
Area (km²): 807,568
Mean Annual Flow (cms): 16,000
Population: 66,000,000

The Irrawaddy is the major river of Myanmar (Figure 5.3), a country which ranks fourth in the world in terms of freshwater capture fisheries, which provide the most important source of protein in the country. Nationally, freshwater fish harvests produce over 1.3 million tons per year and employ approximately 1.5 million people. The Amazon (Figure 5.4) has far lower population numbers and densities than the other two river basins, but still has reported riverine fish harvest of 400,00 tons.[90] Similar to the Mekong, where officially reported harvest levels are one-third that of more comprehensive estimates, it is likely that official harvest levels in both Myanmar and the Amazon basin are underreported.

84 For hydropower increase and fragmentation estimates, see Opperman et al., 2015a
85 ICEM, 2010.
86 Ziv, et al., 2012
87 WWF, 2014; McDonald, et al., 2012
88 Orr, et al., 2012
89 Adapted from ICEM, 2010
90 WWF, "Fish management in the Amazon floodplains."

FIGURE 5.1

Existing (including those under construction) and potential dams in the Mekong River basin.

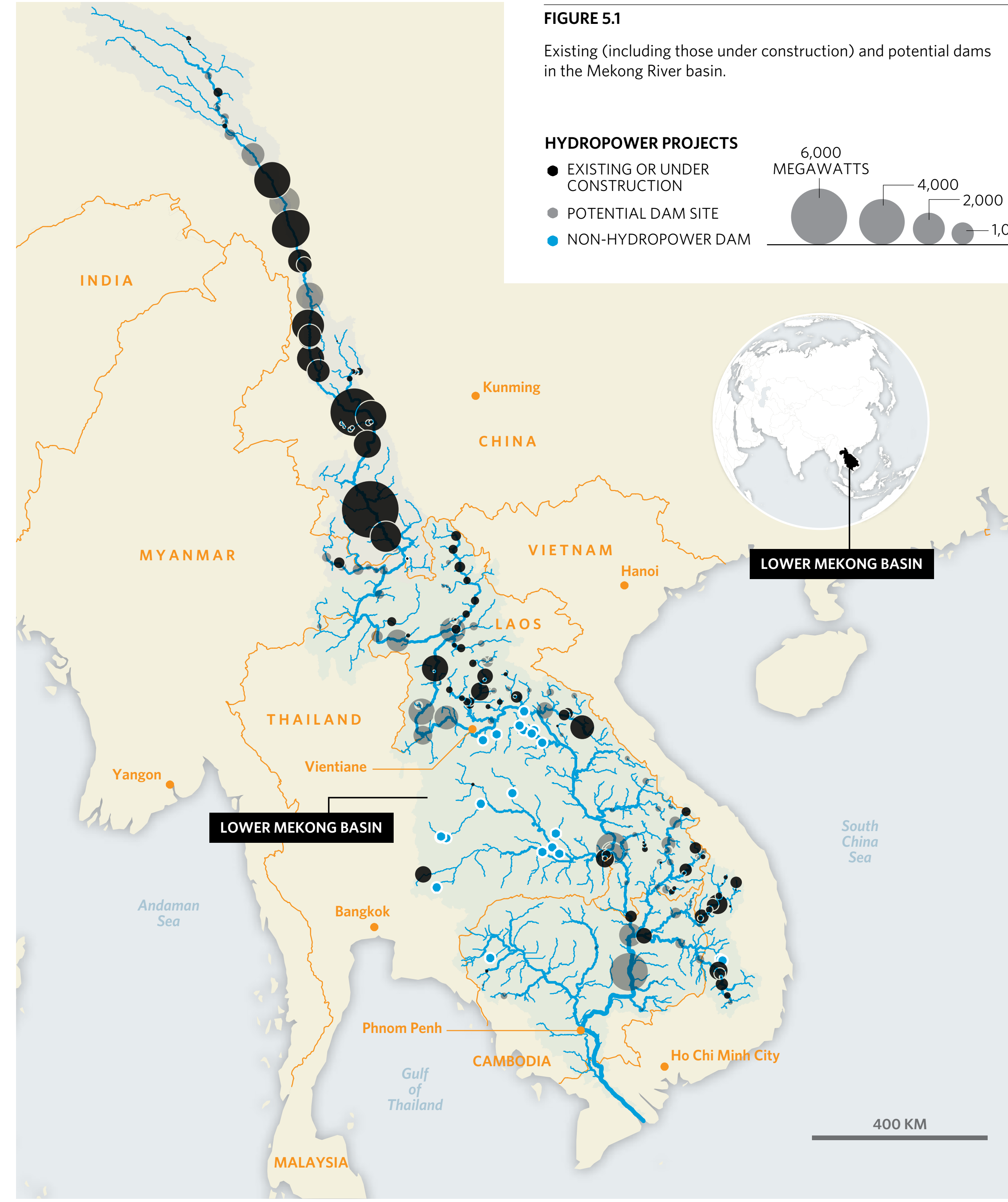


FIGURE 5.2

Projected decline in the biomass of migratory fish in the Mekong basin with development of mainstem dams.[89]

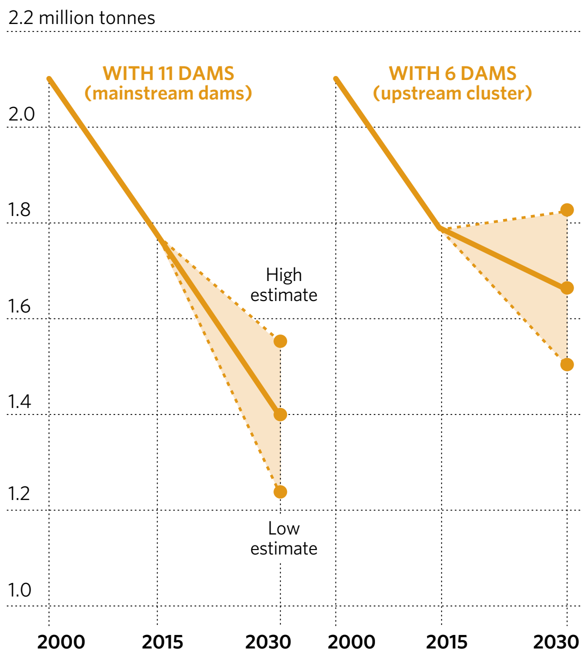
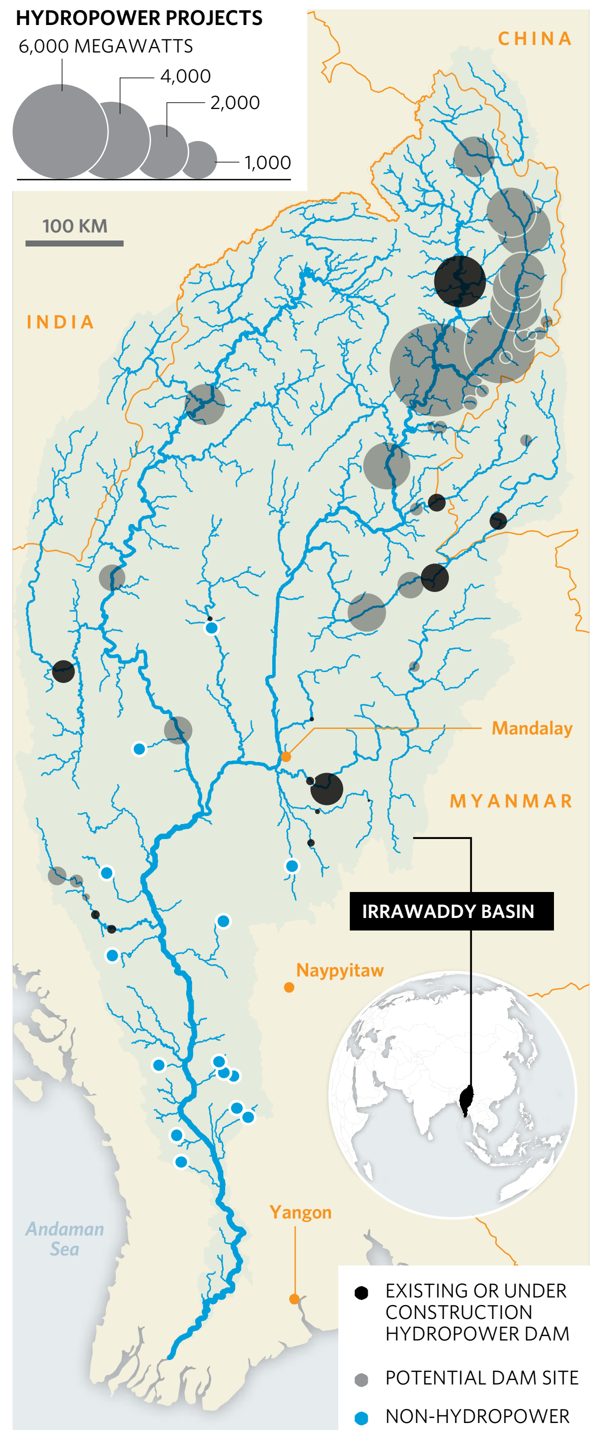


FIGURE 5.3

Existing (including those under construction) and potential dams in the Irrawaddy River basin (Myanmar).



Analysis and results

For these three river basins, we explored a range of impacts from hydropower buildout on the extent of the channel network connected to the lower river systems—and the potential for siting decisions to allow as much migratory fish as possible at various development levels. To do this, we modeled thousands of combinations of dam buildout, drawing on inventories of potential hydropower dams for the basins[91] and, for each combination, quantified the extent of the channel network connected to the mouth of the river. We used this extent of connected channel network as a proxy for habitat for migratory fish that make long-distance migrations from habitats in the lower system to habitats upstream. This approach makes several simplifying assumptions, including that dams are not equipped with effective fish passage. While fish passage is being tried at dams within the Mekong and Amazon basins, in much of the world—and particularly in tropical rivers with migratory fish with high biomass and species diversity—the effectiveness of fish passage has been shown to be limited or is unknown.[92]

91 Zarfl et al., 2015
92 See Brown, et al., 2013; Noonan, et al., 2012

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FIGURE 5.4

Existing (including those under construction) and potential dams in the Amazon River basin.

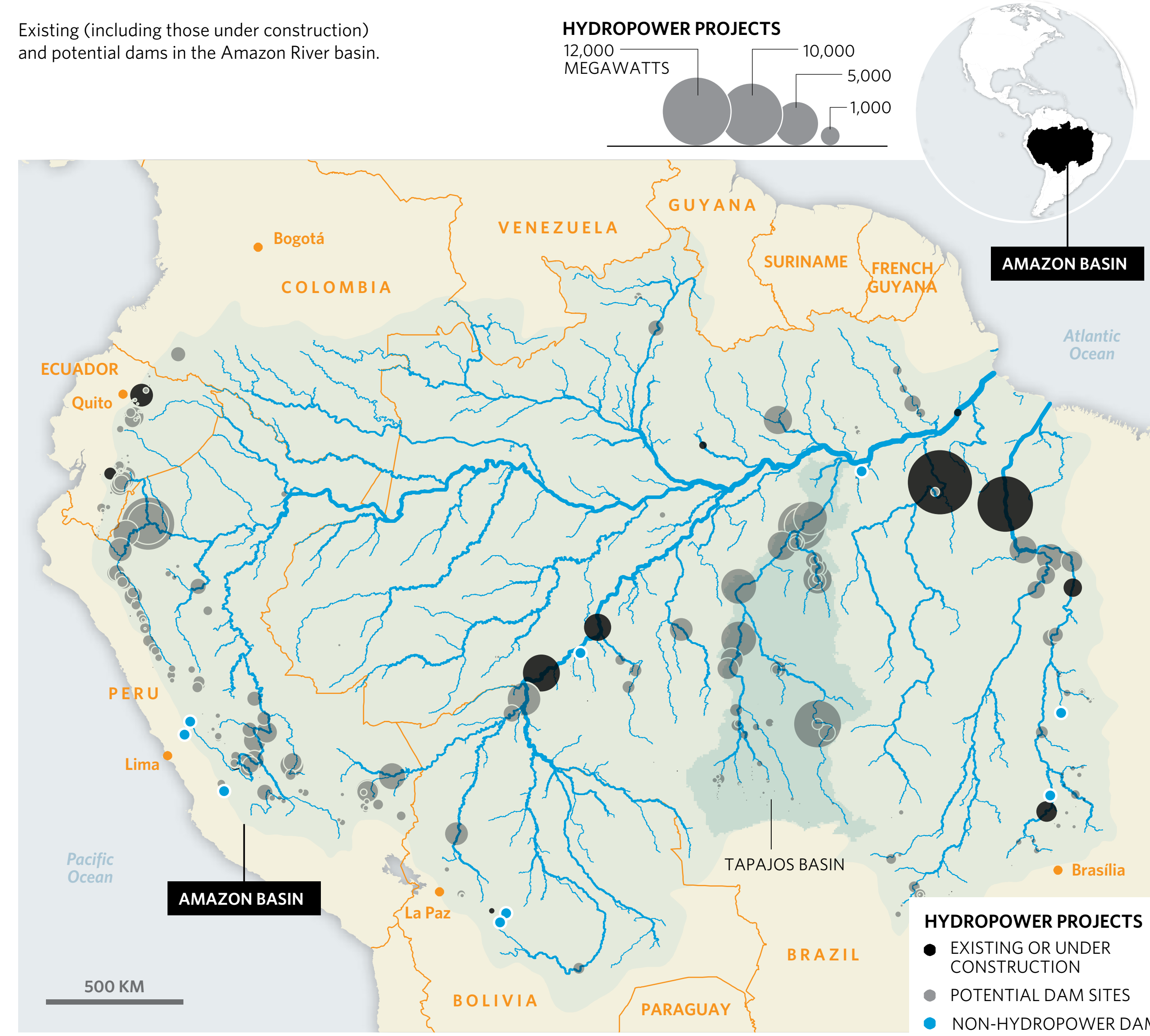
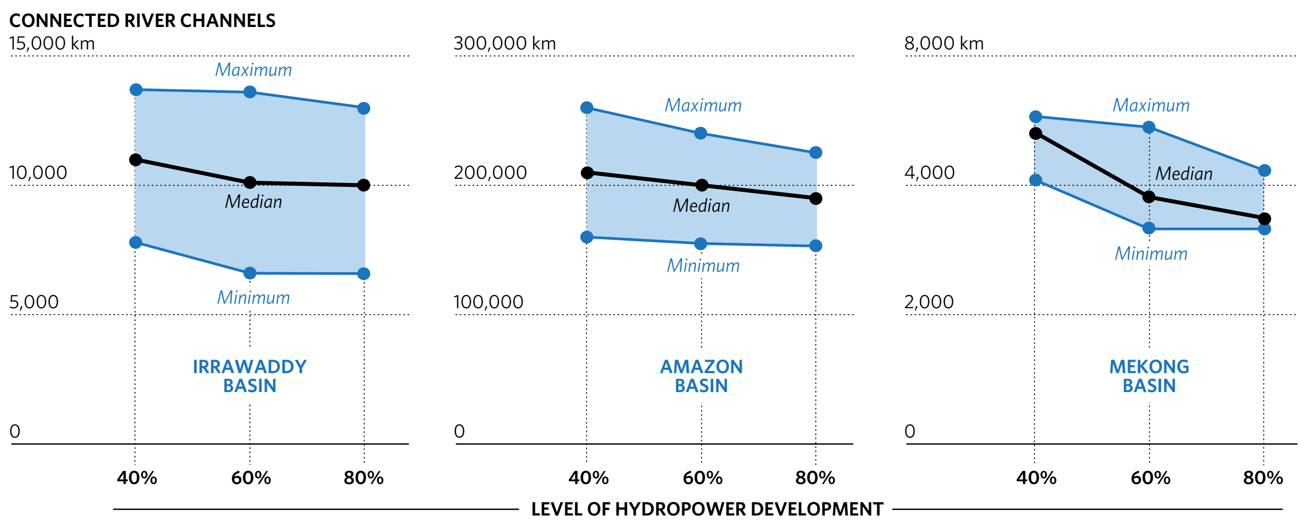


FIGURE 5.5

Extent of channel network connected to the river's mouth (i.e., length of channel connected to lower river and not fragmented by a dam or other obstruction. This can be viewed as an indicator of habitat for migratory fish that undertake long-distance migrations). For each river, thousands of combinations of development options were modeled and the plots show the maximum, minimum and median length of connected river for various levels of hydropower development. Note that kilometers include mainstem rivers and connected tributaries with a mean annual flow greater than 10 cubic meters per second.



Further, migratory fish populations can persist upstream of barriers. However, this analysis is intended to explore the general range of impact on—and potential to maintain—overall connected migratory fish habitat in the main river system. For more details on methods, see the "connectivity case studies" section within Appendix E.

Working at this scale, we did not have financial or economic data or specific existing plans on sequencing of projects to generate a Business as Usual (BaU) case that we could compare against a high-connectivity case (e.g., HbD). Therefore, for these case studies, rather than compare a set of HbD options versus BaU options, we instead explored the distribution of thousands of scenarios to delimit the range of possible outcomes for migratory fish habitat at various levels of hydropower development. In all three basins, there is great range of potential impacts at various levels of development, meaning there is also considerable potential to find development options that reach various capacity or generation targets while minimizing relative impacts to migratory fish for that level of development. In Figure 5.5, compare the maximum line (the most migratory habitat possible for that level of development) with the median and minimum lines, which show the range of distribution of options. In the Mekong, the highest connectivity options were hundreds of kilometers greater than the median connectivity options, while in the Irrawaddy this difference was measured in thousands of kilometers and in the Amazon tens of thousands of kilometers. This analysis did not include financial costs and revenues of the dams and did not consider other impacts beyond connectivity, including impacts of the dams, reservoirs and associated infrastructure on indigenous lands, communities, biodiversity or other resources. Thus, understanding issues of financial feasibility and broader costs and benefits would require more rigorous study. These results are not intended to make specific recommendations on options, but rather are intended to illustrate the important point that, for a given development level, it is likely that system planning that strives to maximize connectivity can result in far better outcomes for connected fish habitat than would arise without planning.

Although the results in this case study do not consider economic viability or the financial competitiveness of projects, we can draw on two examples that have some analysis of project investment costs, the Kouilou-Niari River Basin in the Republic of Congo (Box 5.1) and the Tapajos River in Brazil.

The 2015 Power of Rivers report contained a case study on the Tapajos River (Brazil) which compared 27 development options, including two options that would develop approximately 65 percent of the basin's hydropower capacity. Of these two, a BaU option selected projects based on a least-cost criterion, while the HbD option strived to balance connectivity and capacity. The HbD option had a connected network that was almost 2,000 kilometers longer (80 percent greater) with a total cost, in terms of levelized cost of energy (LCOE), that was only 4 percent more than the BaU least-cost option. The report modeled how global application of this approach to the siting of new dams could protect more connected river habitat and found that, for a level of development approaching predicted levels for 2040, application of HbD to find options that had low impacts on connectivity could result in 100,000 kilometers more connected river networks globally than BaU approaches.[93]

Options with relatively high connectivity are highly unlikely to emerge by chance, but will require strategic selection of certain projects or patterns of development, identifying tributaries, for example, that will be developed for hydropower and identifying other tributaries for protection. Norway and Iceland have conducted national studies that categorize rivers and river reaches in that manner (see Chapter 6). This underscores the value of basin-scale planning, options assessments and realistic analyses of cumulative impacts and costs and benefits. Perhaps most importantly, these approaches can identify projects to avoid because they have particularly high impacts on connectivity. Once such a project is developed, it forecloses many possible viable options for maintaining connectivity. This is clearly illustrated in the Mekong basin by the loss of options for maintaining connectivity, across a broad range of development levels, by the construction of a single high-impact dam (Lower Sesan 2, in Cambodia; see Box 4.2). This dam was identified by Ziv, et al., in 2012 as the single most-damaging tributary dam in the Mekong basin, with an impact on migratory fish almost an order of magnitude higher than the second most impactful dam.[95] Lower Sesan 2 was approved the next year, illustrating the current gulf between scientific guidance and decision making.[96] Dams proposed on the lower mainstem in Cambodia (Sambor and Stung Treng), which are now moving through the planning process, would have even more dramatic negative impacts on system-scale connectivity.

BOX 5.1
Tradeoffs between river fragmentation and forest fragmentation in the Kouilou-Niari River basin

Currently, less than half of people in the Republic of Congo have access to electricity, including less than 5 percent of people in rural areas. Natural gas plants comprise the largest installed capacity (350 MW, nearly 60 percent of national total), followed by hydropower (209 MW, 34 percent).[94] The government of the Republic of Congo seeks to meet rising demand for electricity and views the Kouilou-Niari basin, which currently is undammed, as a potential development area for hydropower. We derived a Business as Usual (BaU) scenario for future development from government documents, which currently envision a single purpose hydropower dam on the mainstem of the river. We explored alternative options (other dams or combinations of other dams) for developing hydropower with similar generation and investment costs as the BaU, but with potentially lower environmental costs (i.e., Hydropower by Design 'HbD' options). To examine potential alternatives to the BaU option, we used an inventory of 13 potential dam sites across the basin with a range of installed capacity. Alternative options and combinations of interacting options were evaluated and compared using a river basin simulation model linked to an automated search algorithm to quantify how each option performed across metrics for river connectivity and for forest fragmentation. For more detail on methods, see "tradeoff analysis" in Appendix E.

The dam in the BaU option is capable of more generation (nearly 4,000 GW hours per year) than any other single dam in the inventory. Thus, all HbD scenarios required more than one dam to have at least comparable levels of generation. The mainstem dam of the BaU is the most downstream dam among all potential dams in the basin and, therefore, all alternative options performed better in terms of connectivity for migratory fish. Conversely, the BaU dam is relatively close to the existing transmission grid and so all alternative options required more transmission lines, which can fragment forests and negatively impact wildlife, include great apes that live in the basin. The best performing (multiple dam) HbD scenario had almost four times greater river connectivity, but almost three times greater length of transmission lines, for similar levels of generation and investment cost. This illustrates a clear tradeoff between one larger dam on a mainstem (with greater river fragmentation but lower forest fragmentation) versus two or more smaller dams higher in the watershed (with less river fragmentation but more forest fragmentation).

93 Opperman, et al., 2015
94 USAID, 2017.
95 Ziv, et al., 2012
96 Opperman, 2014.

Magdalena River Basin: Integrating Models to Identify Strategic Systems Composed of Bankable Projects[97]

Basin Overview

Colombia's Magdalena River flows for 1,500 kilometers from its source in the Andes to the Caribbean Sea (Figure 5.6). With a mean annual flow of 7,300 cubic meters per second, it is the fifth largest river in South America. Spanning nearly a quarter of Colombia's land area, the Magdalena basin (273,000 square kilometers) is the economic, social and cultural heart of Colombia. It constitutes Colombia's most important region from several perspectives:

Population: 36 million people live in the basin, representing 75 percent of Colombia's total population.

Economy: Supports 86 percent of Colombia's GDP, 75 percent of the nation's agricultural production and 90 percent of its coffee production.

Energy: Generates 70 percent of hydropower energy and is the source of 90 percent of its thermoelectric energy.

Biodiversity: Supports 250 species of mammals, 800 species of birds and 400 species of amphibians. Of the 213 identified fish species, over half are endemic. Nearly a quarter of land cover in the basin is considered natural or pristine habitat and 7 percent of the basin is protected under the national parks system (UAESPNN).

Indigenous Communities: Approximately 140,000 indigenous people live in the basin, mostly within 143 indigenous reserves that span 775,000 hectares.

The Magdalena basin currently has 35 medium and large hydroelectric sites that produce an average of 33,400 GWh per year from an aggregate installed capacity of 6,673 MW. Approximately 100 other potential sites in the Magdalena, with an aggregate capacity of 24,000 MW, were identified through a basin study in the 1970s.[98] Seven of those projects are larger than 500 MW and two of those, with a total capacity of 2,800MW, are currently under construction.

Magdalena 'Business Case' Introduction

This Business Case demonstrates how different modeling methodologies can be combined into a single decision-making framework, with the goal of generating a 'common language' which accurately frames tradeoffs and alternatives for decision makers. Further, this approach can increase the transparency of decisions and improve access to information for stakeholders. In collaboration with PSR, a Brazil-based energy consultancy in software development and modeling analyses, we brought together four basic modeling families (see Figure 4.1) to provide an integrated analysis, spanning financial returns, energy targets and cumulative impacts across resources that have value to a range of important stakeholder groups. This research drew upon comprehensive data on environmental and social resources and stakeholder perspectives, compiled by The Nature Conservancy over several years (see Appendix B).

Through this Business Case analysis, we compared alternative buildout scenarios that selected from 97 potential dam sites as catalogued in the 1979 hydropower master plan Study of the Electric Energy Sector. This study is broadly considered to be reliable by government and developers. We used PSR's model, HERA, to apply modern dam design and costing frameworks to these sites, described in detail in the "Magdalena case study analysis" section in Appendix E.

Note that the scenarios presented in the following pages do not constitute a specific recommendation for hydropower buildout in the Magdalena basin. Rather, we use these analyses to explore the potential financial, economic and environmental benefits derived from a HbD approach compared with BaU practices.

As discussed in Chapter 4, HbD can produce two sources of financial value—optimization through system engineering and improved risk management. Below, we describe scenarios to explore these sources of value.

97 More detail on the Magdalena basin can be found in Appendix B.
98 DNP, 1979.

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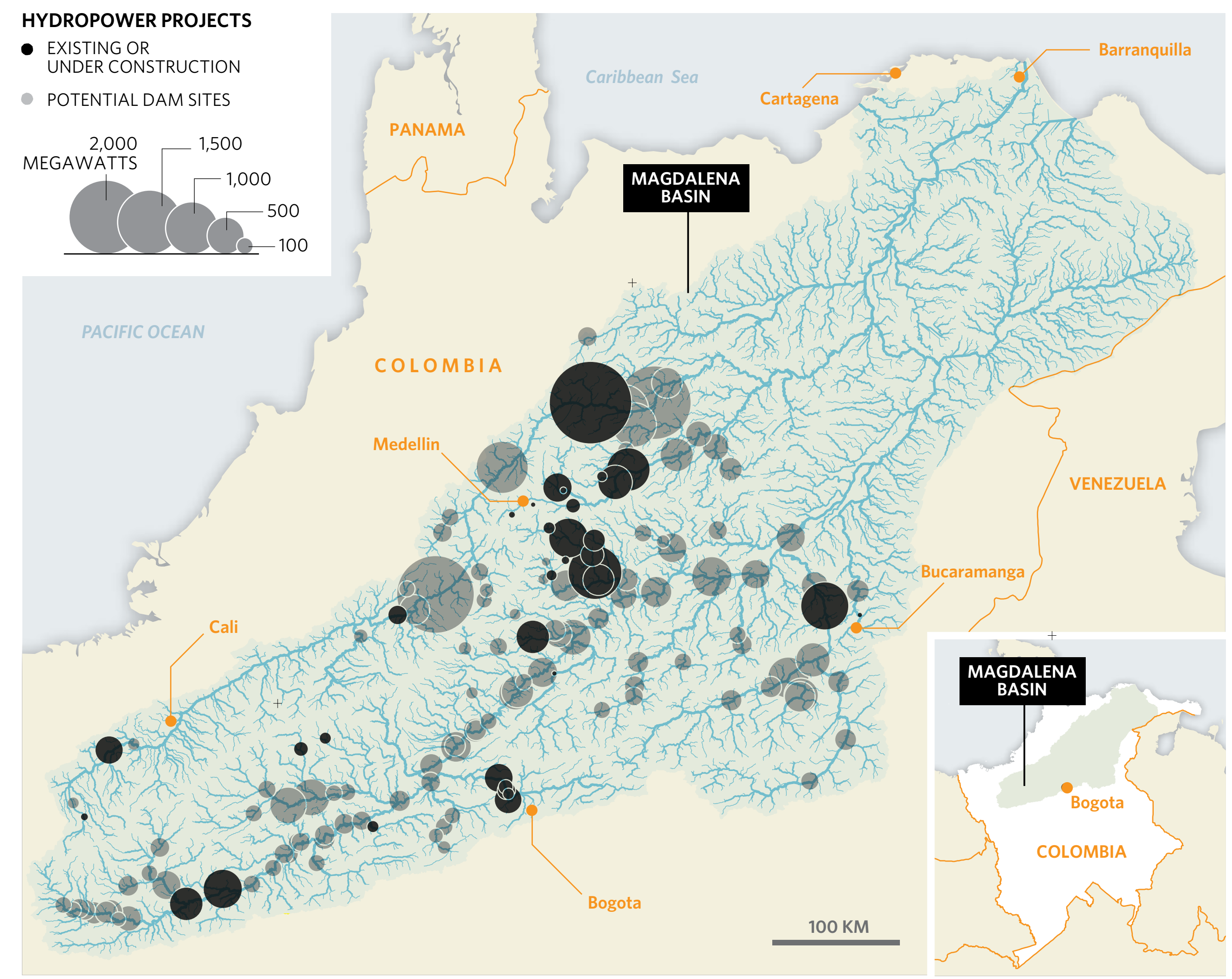
FIGURE 5.6

Map of the Magdalena River Basin (Colombia) with existing and potential hydropower dam sites.



Financial Driver #1: Optimization via System Engineering

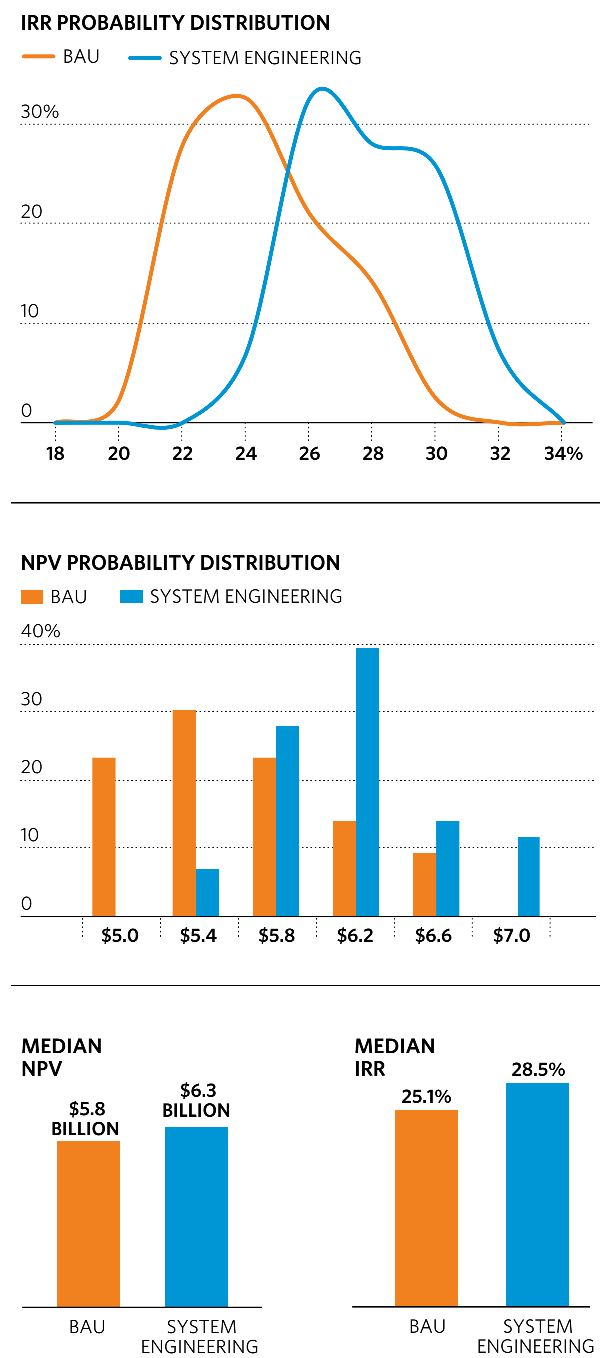
For the case of the Magdalena, we formulated a Business as Usual (BaU) scenario designed to mimic how current development decisions are made in the basin. Colombia's hydropower development process relies on independent project development initiatives made in response to periodic auctions by the government for additional energy capacity. Currently there is no centralized or coordinated planning, with decision-making for project site identification distributed among multiple competing non-coordinated market agents.

Developers generally prioritize projects with the highest Net Present Value (NPV). The BaU algorithm mimics this development framework by constructing sites on an iterative basis by prioritizing those with the highest NPV. The selection and construction of a site potentially changes the conditions for all future sites by updating the river cascade topology after each plant is installed. The model then recalculates NPV values for the remaining sites and selects the project with the highest NPV among those. This continues until a target generation level is reached.

We then examined alternatives to the BaU scenario. First, we developed a System Engineering scenario, which optimizes the basin buildout in an integrated fashion. Rather than selecting sites sequentially, maximizing project-level NPV at each step, the system engineering scenario seeks to optimize NPV for an overall system that can meet the same energy generation target as the BaU. By considering how projects interact with each other (e.g., through flow regime) and through a holistic assessment of costs and dam design, this approach can capture system-scale efficiencies.

FIGURE 5.7

Distribution of project-level Internal Rate of Return (IRR) and Net Present Value (NPV) for BaU versus System Engineering scenarios of hydropower development in the Magdalena Basin. The median NPV and IRR for a scenario describes the median value from a number of Monte Carlo simulations of the aggregated cashflows from all projects in that scenario.



The optimization for the system engineering approach is solely designed to maximize basin-level profit and does not integrate social or environmental impacts and resulting impacts on project-level risk. Electricity revenues are based on long term Power Purchase Agreement contracts (US$56 per MWh) and 'reliability charge payments' applied to the firm capacity of each plant (US$15 per MWh). Electricity surplus (positive difference between energy generation and contract volume) or shortfall (negative difference) is cleared in the Colombia power market at the prevailing market price.

The System Engineering approach to developing a portfolio yielded a 9.3 percent increase in expected NPV of profitability to developers (defined as revenues minus costs, over a 35-year timeframe, discounted at a 9 percent rate). A related measure, Internal Rate of Return (IRR), increased from 25.1 percent in the BaU case to 28.5 percent in the System Engineering Case (Figure 5.7 and Table 5.2). Both the IRR and NPV indicators suggest that the accumulation of project-level decisions in the BaU leaves money on the table from a financial perspective by failing to capture a range of system-scale efficiencies which can only be identified through a comprehensive basin planning process.

TABLE 5.2

System-scale performance of the BaU scenario and the System Engineering scenario.

Scenario	BaU	System Engineering
Available Projects	97	97
Selected Projects	4	11
Installed Capacity (MW)	5,365	4,646
Mean Yearly Production (GWh)	29,191	29,651
Firm Energy (MW average)	2,153	2,176
Mean Yearly Firm Energy (GWh)	18,859	19,063
Environmental Impacts Index	61%	61%
Social Impacts Index	80%	48%
NPV (US$bn)	$5.8	$6.3
IRR (%)	25.1%	28.5%

Financial Driver #2: Optimization via Social and Environmental Risk Reduction

The second driver of financial value involves incorporating the risk contribution from social and environmental factors into projections for construction-related cost overruns and time delays. Social and environmental impacts can lead to conflicts that contribute to the delays and cost overruns that are very common for hydropower projects (see Chapter 3).

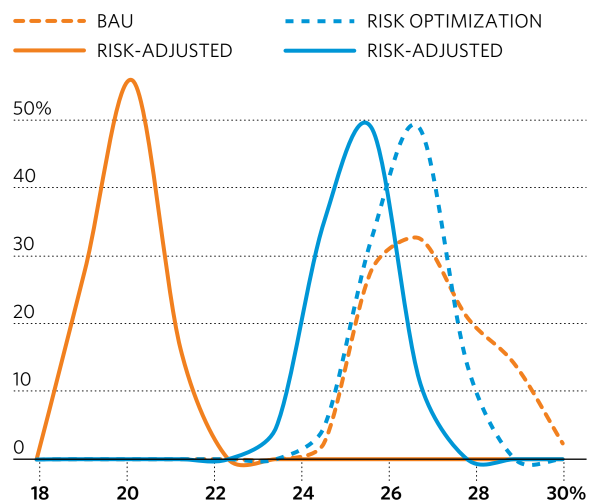
To frame this analysis, we identified peer-reviewed data sets indicating the overall construction cost and time overruns for hydropower projects[99] and then transformed the associated distribution curve based on an environmental and social contribution factor (i.e., the percentage contribution made to the overrun by environmental and social risks). In this analysis, we assumed this to be 30 percent[100].

We then matched each project to an "environmental and social risk score" that defines what kind of time delay and/or cost overrun would be expected for the project. These data and construction of this risk score index were informed by several years of TNC's engagement with the basin and integrates a variety of environmental, social, demographic and economic variables. Some of these variables include mining areas, protected natural reserves, sensitive ecosystem zones (such as dry forest), anticipated population resettlement, indigenous community territories and post-conflict zones (see Appendix B). The risk score was weighted approximately 80 percent by social risk and 20 percent by environmental risk, reflecting the reality in Colombia that conflicts over social resources tend to contribute more to project conflict and delay than do environmental impacts (note, however, that many social impacts arise from environmental impacts).

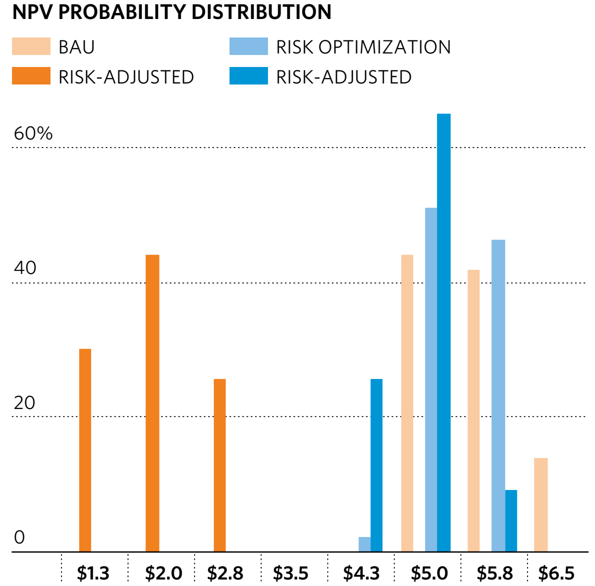
FIGURE 5.8

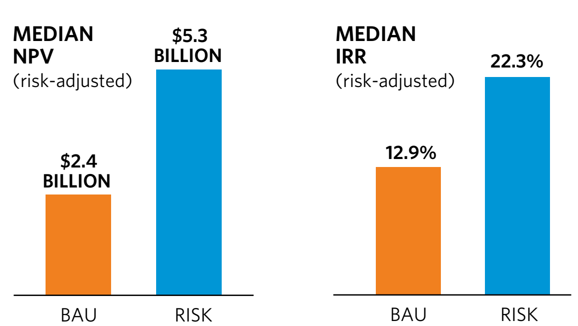
Distribution of project-level Internal Rate of Return (IRR) and Net Present Value (NPV) for BaU versus Risk Optimization scenarios of hydropower development in the Magdalena Basin. The median NPV and IRR for a scenario describes the median value from a number of Monte Carlo simulations of the aggregated cashflows from all projects in that scenario.

IRR PROBABILITY DISTRIBUTION



NPV PROBABILITY DISTRIBUTION





The Risk Optimization scenario highlights the value of prior consultation with social and environmental interests and demonstrates how incorporating a better understanding of those impacts into site selection can reduce risks and result in improve project-level financial performance. The first set of BaU results were risk blind, so we sought to understand how a more-comprehensive assessment of risk could affect the BaU projects. We modeled the potential for environmental and social impacts to translate into delays and cost overruns by applying a risk penalty (the environmental and social risk score) to the projects selected through the BaU approach. Through this, we generated a new set of NPV and IRR scores for the BaU portfolio (Figure 5.8 and Table 5.3). Note that the Risk Optimization scenario also incorporates the basin-scale engineering benefits generated by the Engineering Optimization scenario.

We then selected a "Risk Optimization" portfolio of projects—also intended to meet the same generation target as BaU—that incorporated projections of how risk could affect NPV before sites were selected (i.e., on an *ex-ante* basis). Projects within the BaU scenario were heavily impacted by the risk penalty with a considerable decline in NPV and IRR values (see the leftward shift from BaU to risk-adjusted BaU in Figure 5.8). Large, complex projects with many negative impacts were projected to suffer from substantial time delays and cost overruns. By contrast, projects within the Risk Optimization scenario, which incorporated project risk on an *ex-ante* basis into the project selection process, showed a relatively small decline once we modeled the impact of risk on project performance. The Risk Optimization scenario selected far more projects (18) than did the BaU scenario (4), reflecting that the largest hydropower projects often are associated with the highest degree of social and environmental risk.

TABLE 5.3

System-scale performance of the BaU scenario and the Risk Optimization scenario.

Scenario	BaU	Risk Optimization
Available Projects	97	97
Selected Projects	4	18
Installed Capacity (MW)	5,365	4,686
Mean Yearly Production (GWh)	29,191	29,412
Firm Energy (MW average)	2,153	2,220
Mean Yearly Firm Energy (GWh)	18,859	19,451
Environmental Impacts Index	61%	58%
Social Impacts Index	80%	26%
NPV (US$bn): Risk-Adjusted	$2.4	$5.3
IRR (%): Risk-Adjusted	12.9%	22.3%

99 Sovacool, et al., 2014.
100 This estimate was informed by experience of members of the research team evaluating risk profiles of hydropower projects through application of the Hydropower Sustainability Assessment Protocol (IHA, 2010).

The Hydropower by Design Case: Harnessing Financial Drivers to Pay for Enhanced Public Benefits

As summarized in Chapter 4, the financial benefits of HbD can potentially be used to "pay for" more strategic outcomes. To explore the potential for HbD financial value to promote these broader objectives, we also developed another set of scenarios, organized as a set of Narratives that limit basin buildout to pre-defined development corridors (e.g., 'working' versus 'pristine' river segments) with the intent of accomplishing specific environmental and social objectives.

Background for Narrative Scenarios

Given the lack of existing coordination for site identification among governmental functions, the Conservancy convened a workshop series with Colombia's National Authority for Environmental Licensing (ANLA), along with other agencies including the Ministry of Environment and Sustainable Development (MADS), Ministry of Mining and Energy (MINIMAS), the National Energy Planning Unit (UPME), regional environmental authorities and representatives of major energy companies. The objective of the discussions was to outline potential hydropower expansion scenarios that would focus development within certain areas while also focusing protection on other areas. The resulting Narratives can be translated into scenarios within this modeling framework through simple rule sets that bound some site selection decision. For example, the rules may constrain development from happening within a certain region or river reach or limit development to tributaries to avoid fragmenting the mainstem, or avoiding displacement. For this case study, we focus on three Narratives:

Narrative A: Avoids development with the Magdalena's main functional network, including the mainstem and a set of free-flowing tributaries (Saldaña, Carare, Cesar, San Jorge, etc.). Rivers outside of this network are defined as 'working rivers.'

Narrative B: Includes the same restrictions as Narrative A, but also avoids projects along an additional list of important rivers including the Cauca, Sogamoso, Alto Magdalena and Páez.

Narrative B and Meet Production Target: Forces sub-economic projects via higher energy tariffs to still allow for meeting the approximately 30,000 GWh annual generation target.

As expected, the Narratives resulted in far lower impacts, as reflected in the environmental and social indices (see Figure 5.9 and Table 5.4). NPV and IRR were either comparative or superior in Narratives A and B relative to BaU, although Narrative B has a lower total count of financially viable projects and hence meets a lower annual power generation target. Intriguingly, if some of this financial surplus is re-allocated to the sub-economic projects through differential power pricing ("Narrative B & Meet Production Target") it is still possible to roughly meet the energy production target. Narrative B could be a key part of meeting that energy target if generation from other renewable sources, such as wind and solar, were increased, an integrated approach to renewable energy planning as described in the Sarawak case study.

FIGURE 5.9

Performance relative to BaU for energy, financial, environmental and social metrics for the Risk Optimization scenario and three narratives based on specific conservation "narratives." Note that "positive" bars indicate improved performance (e.g. a positive bar for "social index" indicates lower negative impacts on social values).

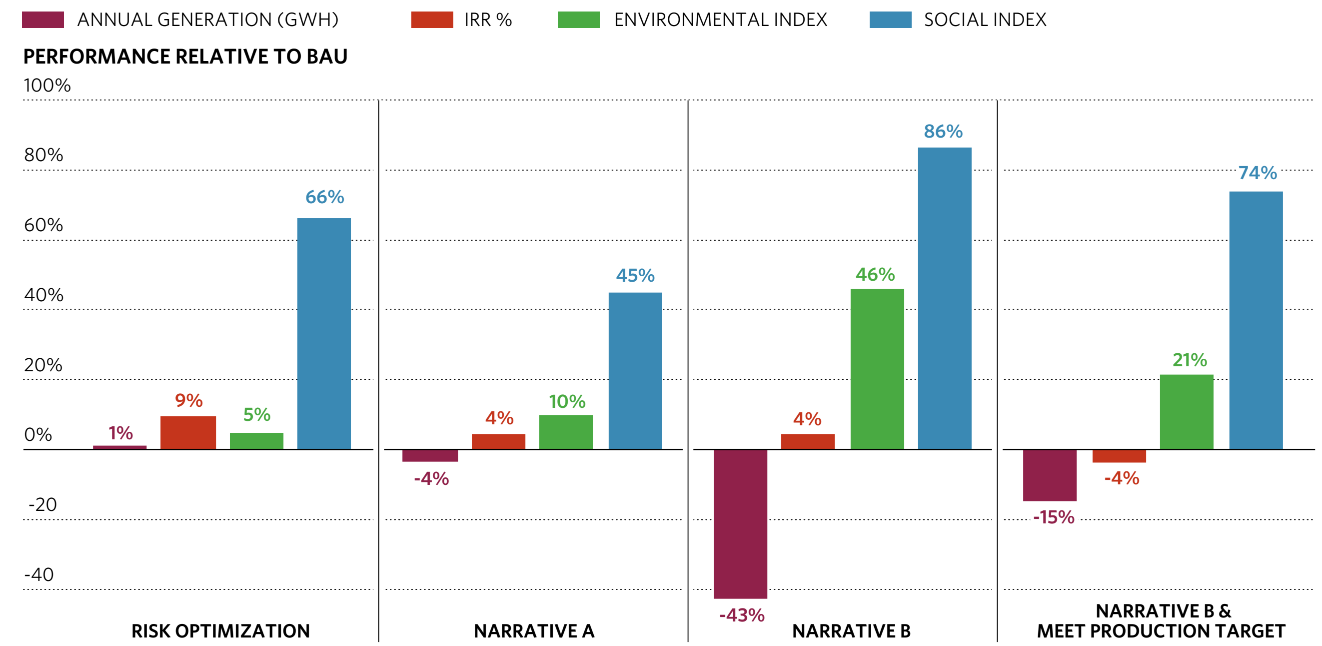


TABLE 5.4

System performance for the BaU scenario compared to the Risk Optimization scenario and three narratives based on specific conservation "narratives."

			NARRATIVE		
Scenario	**BaU**	**Risk Optimization**	**A**	**B**	**B & Meet Prod. Target**
Available Projects	97	97	31	30	30
Selected Projects	4	18	8	13	29
Installed Capacity (MW)	5,365	4,686	4,690	2,852	4,370
Mean Yearly Production (GWh)	29,191	29,412	28,156	16,621	24,811
Firm Energy (MW average)	2,153	2,220	2,197	1,304	2,028
Mean Yearly Firm Energy (GWh)	18,859	19,451	19,244	11,425	17,761
Environmental Impacts Index	**61%**	**58%**	**55%**	**33%**	**48%**
Free River Length (km)	*8,588*	*8,228*	*8,548*	*8,571*	*8,458*
Degree of Regulation (%)	*16%*	*10%*	*12%*	*9%*	*11%*
Sediment Transport Alteration (%)	*40%*	*46%*	*40%*	*39%*	*43%*
Dry Forest Affected (Ha)	*1,093*	*344*	*929*	*-*	*10*
Wetlands Affected (Ha)	*4,402*	*1,108*	*3,995*	*402*	*402*
Social Impacts Index	**80%**	**27%**	**44%**	**11%**	**21%**
Population Resettled	*26,777*	*8,280*	*22,234*	*1,503*	*4,608*
Productive Lands Affected (Ha)	*24,938*	*6,226*	*15,946*	*5,133*	*9,966*
Indigenous Population Affected	*-*	*-*	*-*	*-*	*-*
Mining Areas Affected (Ha)	*6,949*	*4,943*	*4,651*	*1,726*	*2,927*
Post-Conflict Zones Affected	*14,922*	*796*	*949*	*504*	*759*
NPV (US$bn): Risk-Adjusted	$2.4	$5.3	$3.9	$2.1	$0.2
IRR (%): Risk-Adjusted	12.9%	22.3%	17.3%	17.2%	9.3%

Conclusions

In the scenarios described here, the financial benefit via system engineering and avoided environmental and social risk accrues to investors through enhanced NPV and IRR. However, so long as the projects remain financially viable, it is possible to instead transfer this financial benefit from investors to the public interest, thereby building a bridge to government so it can afford to be strategic about its hydropower buildout.

- Lower energy tariffs to electricity consumers
- Paying for alternative dam design and operations to provide other public benefits
- Alternative siting to avoid population displacement
- Environmental flows to maintain or restore downstream ecosystems

Furthermore, we should note that in many ways the above scenarios represent conservative estimates regarding the financial benefits derived from basin-scale planning. The financial analysis only considers risks during the construction period. Substantial time delays and cost overruns, triggered by social and environmental risk, can also occur during the project design phase. Further, this analysis doesn't capture the potential risk of full project cancellation—though relatively rare, this is obviously a major risk of large, complicated projects (see Box 3.2).

Additionally, candidate sites were limited to those identified in the 1979 inventory and our modeling was limited to designs that match the dam heights recommended in that inventory. The HERA model used in this study can also generate new dam inventories, based on topography, hydrology and risk factors and then explore a full range of dam heights and designs for each site. All variables can be combined into an overall system optimization. In other words, a full application of modern tools might result in an improved dam inventory of bankable projects that provides even greater flexibility for achieving other economic objectives and meeting sustainability goals.

Finally, this analysis was limited to hydropower as a solution to meeting a generation target and did not consider the potential for a mix of renewable sources to meet that target. Future work incorporating this greater complexity will increase the likelihood for capturing value and achieving more sustainable outcomes, further highlighting the potential of integrated energy planning and using system perspectives to guide site selection.

Whole energy system planning: comparing hydropower and decentralized alternatives for Sarawak (Malaysian Borneo)[101]

Background: Borneo and the Sarawak Corridor of Renewable Energy

The rapid economic growth in Southeast Asia in the new millennium has led to a dramatic increase in the development of large hydropower projects in river basins including the Yangtze and the transboundary Mekong. In Malaysia, the state government of Sarawak is implementing a development program called the Sarawak Corridor of Renewable Energy (SCORE) with a predominant emphasis on hydropower.[102] Sarawak, located along the northern coast of the island of Borneo (Figure 5.10), is the poorest and most rural state in Malaysia. The state government is hoping that inexpensive electricity will attract manufacturing and promote economic development. The current peak annual energy demand in Sarawak is 1,250 MW, met by a mix of diesel, coal and natural gas generation either operated or purchased by the state utility company. At least 12 large hydroelectric dams and two coal power plants, together constituting 9,380 MW of capacity, are scheduled to be built before 2030.[103]

Although those dams could meet energy demand, Sarawak supports globally significant ecological and cultural values and development of the proposed dams would cause significant social and environmental impacts, including the displacement of approximately 100,000 indigenous people and loss of at least 2,425 square kilometers of direct forest cover loss.[104] Six dams are scheduled to be completed by 2020, including three already under different stages of development (see Figure 5.10).[105] In 2012 the 2,400 MW Bakun dam became operational. The dam's reservoir submerged 700 square kilometers of land and displaced about 10,000 people. In 2013, the 944 MW Murum Dam was completed and the 1,200 MW Baram Dam was scheduled for construction.

FIGURE 5.10

Sarawak on Malaysian Borneo.

© TIM LAMAN/NATIONAL GEOGRAPHIC CREATIVE (SARAWAK RIVER, MALAYSIA)

However, the government announced a moratorium against the Baram Dam in September of 2015, largely in response to local and international pressure. On March 21, 2016 a legal decision to solidify this position was announced: the Government of Sarawak reaffirmed indigenous ownership of the land for the dam site, reversing a previous classification that would have allowed the developers to proceed. This decision demonstrated that communities can advocate effectively to protect their interests. It also demonstrated the value of science communication. Research published by the Renewable and Appropriate Energy Laboratory (University of California, Berkeley) had identified financially viable commercial power production alternatives for the state and the government's awareness of realistic energy alternatives facilitated the decision to cancel Baram Dam. This case study summarizes that research and illustrates how expanding the search for options to include other generation sources can reveal alternative pathways that may have a better mix of balanced outcomes and avoid negative impacts that are too high.

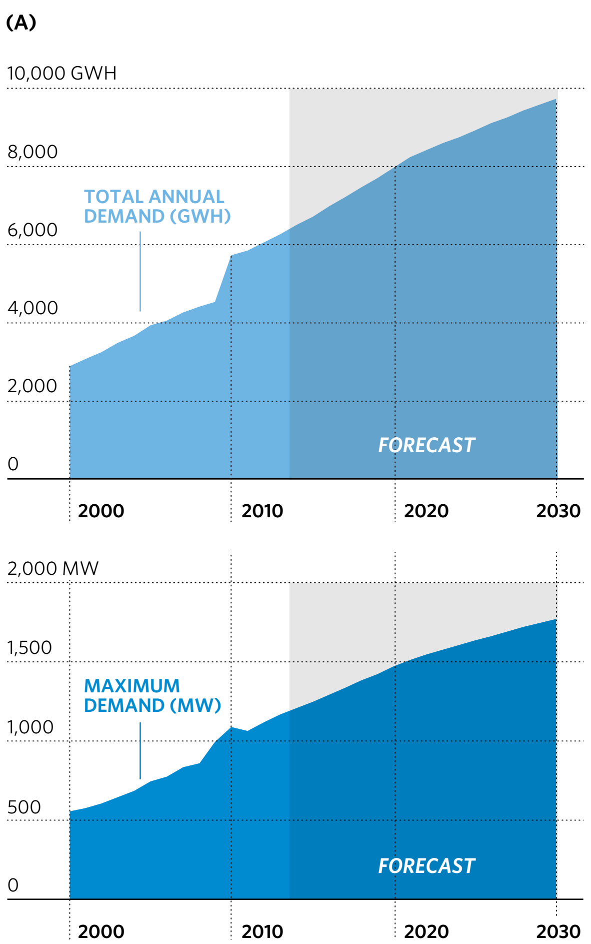
Balancing the need for large infrastructure with locally appropriate energy solutions presents very real governance and technical challenges. While there is widespread agreement on the need for a planning approach that combines large infrastructure and decentralized systems, most national energy or electrification strategies contain minimal consideration of this integration and little information on the potential for decentralized solutions is available for public discourse.[106] This case study is part of a broader research program to address this gap and contribute to the literature on management of energy transitions. In this study, we adapted a long-term energy simulation and analysis tool and demonstrate its use in comparing energy options in Sarawak, including alternatives to a BaU approach that emphasizes large hydropower. This region provides an illustrative case study for the potential for whole-system energy planning because it is a growing economy making a transition toward industrialization, has a range of generation options, including renewables, and has globally important cultural and environmental values that can be impacted in different ways by different energy development pathways.

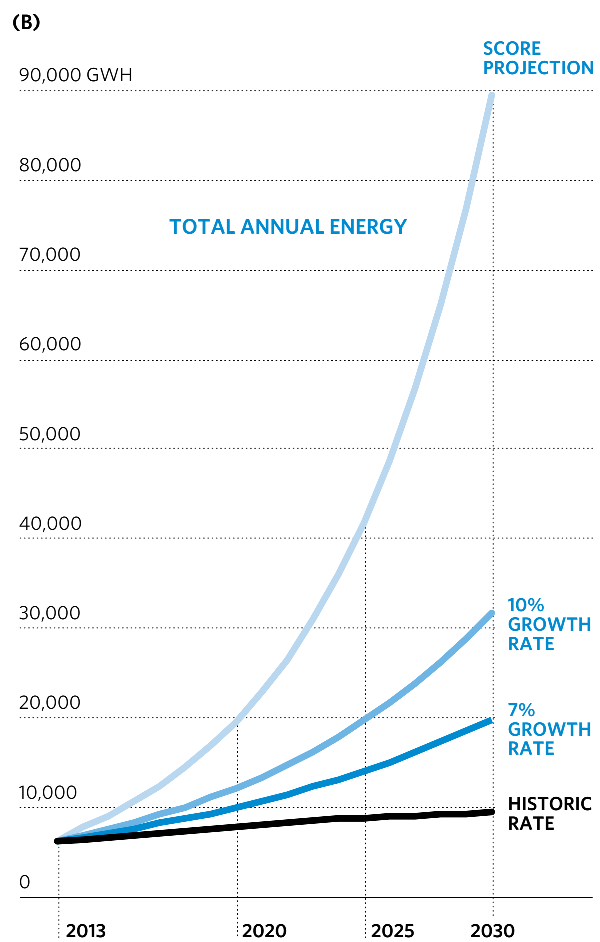
101 Lead authors: Rebekah Shirley and Daniel Kammen
102 SCORE, "What is SCORE?"
103 Sovacool and Bulan, 2012.
104 Fonds, 2012.
105 Suruhanjaya Tenaga (Malaysia Energy Commission), 2012.

106 Tenenbaum, et al., 2014.
107 Sarawak Energy Berhad, 2010.

FIGURE 5.11

(A) Growth in demand for total electricity (above) and maximum (below) for Sarawak since 2010 and then projected to 2030 following the same growth rate. (B) Four scenarios of future growth in electricity demand for Sarawak.





Analysis: Using Grid Simulation to Compare Cost and Benefit of Viable Energy Mixes

To date, there has been little quantitative analysis of Sarawak's energy options or cost and benefit tradeoffs and this lack of information and public discussion are major barriers to comprehensive energy planning. This case study addresses the question: What are feasible alternative energy futures for Sarawak that meet future energy demand for the local population given priorities of (a) cost, (b) reliability and (c) environmental impact?

In this case study we describe a model of the proposed energy system simulated under different future scenarios using the commercial energy market software PLEXOS. Using this commercial power-simulation application we prepared a long-term capacity energy expansion model for the state of Sarawak. We first mapped available primary energy resources, existing generation and potential generation options. In addition to the existing plants, these generation sources include hydropower and decentralized sources such as solar photovoltaic (PV), conversion of palm oil mill effluent (POME) and biomass gasification. Using data on these sources, we then analyzed optimal system configurations for Sarawak over the long term, based on existing generation and resource and operability constraints, incorporating metrics for the costs of greenhouse gas emissions. We built four demand-growth scenarios and four policy scenarios to explore a range of economic assumptions and then modeled the resulting cost, performance and environmental tradeoffs through linear optimization.

The SCORE plan assumes a nine-fold increase in electricity demand between 2010 and 2020 (from 5,921 GWh to 54,947 GWh), which represents a 16 percent per annum growth rate. In terms of installed capacity, this translates to an expansion from 1,300 MW in 2010 to between 7,000 MW and 8,500 MW in 2020.[107] We modeled both this SCORE growth assumption and a conservative historic 2 percent per annum growth assumption. We then modeled two intermediate growth rates: 7 percent per annum and a more ambitious 10 percent per annum (see Figure 5.11). We also incorporated policy scenarios such as the establishment of a Renewable Portfolio Standard (RPS) or Feed-in Tariff (FiT), policies happening elsewhere in Malaysia, to observe the effect of policy instruments on the optimal energy mix. For more details, see "Sarawak methods" in Appendix E.

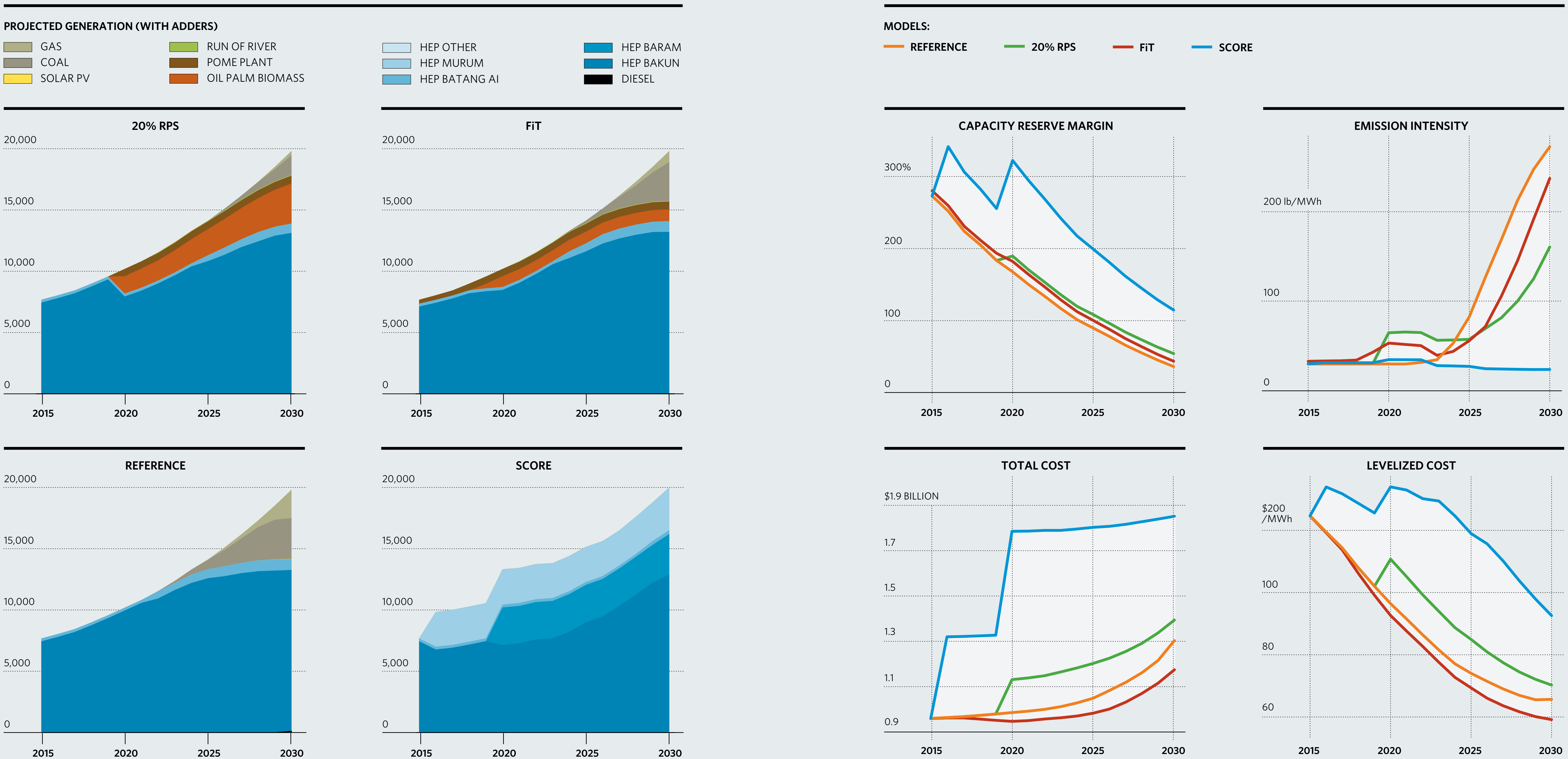
Results: Incentive Schemes Can Significantly Influence Most Optimal Energy Mix

We found that Sarawak's current installed capacity, including Bakun, already exceeds expected demand in 2030 under the historic growth assumption. So, using this growth forecast, the results showed no additional buildout and no investment differences across policy scenarios. The Bakun Dam itself can provide more than 10,000 GWh per annum. Under a 7 percent electricity demand growth assumption, Bakun's generation could meet half of expected demand by 2030. Even under the more aggressive 10 percent growth assumption, Bakun alone would satisfy a third of demand in 2030. Completion of the two additional dams currently under construction (Murum and Baram) would result in an oversupply relative to 2030 demand projected with 7 percent growth, leading to a large excess capacity. Under the 10 percent growth projection, this level of generation would require a marginal amount of additional generation.

The other scenarios show that decentralized generation sources, including PV, biomass gasification and POME conversion, can all contribute to meeting future demand. Both the FiT and RPS scenarios call for the buildout of over 450 MW of biomass waste capacity. The overall total cost per year is quite similar across the other scenarios, though the various cost components differ. We find the Reference and FiT scenarios have the lowest total cost and levelized costs across the fifteen-year time horizon (Figure 5.12).

FIGURE 5.12

Generation profile, cost components and generation characteristics of scenarios under 7 percent demand growth.



The SCORE scenario has a higher total cost and a higher levelized cost than all other scenarios. While it has a low fuel cost and emissions cost, the high annual build cost and associated fixed costs are high. This is because the system is over-built. Building three dams causes the Capacity Reserve Margin to rise to over 300 percent and the reserve margin stays well above 100 percent in 2030, much higher than the 15 percent minimum constraint imposed. The SCORE scenario has 6 GW installed capacity by 2030, almost 33 percent greater than any of the other scenarios which each have roughly 4 GW installed. Nevertheless, the SCORE scenario has one of the lowest emissions production and emission intensity rates. The overall total cost per year is quite similar across the other scenarios, though the various cost components differ. We find the Reference and FiT scenarios have the lowest total cost and levelized costs across the fifteen-year time horizon.

When we applied low future renewable energy technology costs (Biomass: US$1,500/kW; POME: US$2,000/kW, Solar PV: US$1,100/kW and Wind: US$2,210/kW) it changed the resulting generation matrix in the FiT scenario and called for as much Palm Oil Biomass generation and PV generation as possible, with no conventional generation chosen. These results show that renewable resources, including solar and biomass waste, can contribute to the generation mix at lower cost and environmental impact than additional dam construction over the long term and especially when supported by incentive schemes.

We considered the additional cost of environmental impacts, including greenhouse gas (GHG) emissions and direct loss of forest land, as follows: We applied emissions factors to generation and assumed that a carbon price of US$10/tonne CO_2-eq is applied in 2015. A charge based on Forestland Value (FLV) was applied as a fixed charge per kW-year. We found that inclusion of the carbon adder changed the optimal configurations selected, while the land-value adder had little significant impact on the choices made. Emissions caused total annual cost in 2030 to be 4 percent greater for the SCORE scenario while increasing the total cost by a much larger margin for other scenarios. The FLV adder caused no observable change in any cost property for any scenario. Inclusion of the environmental-cost adders also caused fuel switching: the 20 percent 2020 RPS scenario again built out 490 MW of biomass gasification and POME biogas capacity while the FiT scenario switched to 596 MW of Solar PV.

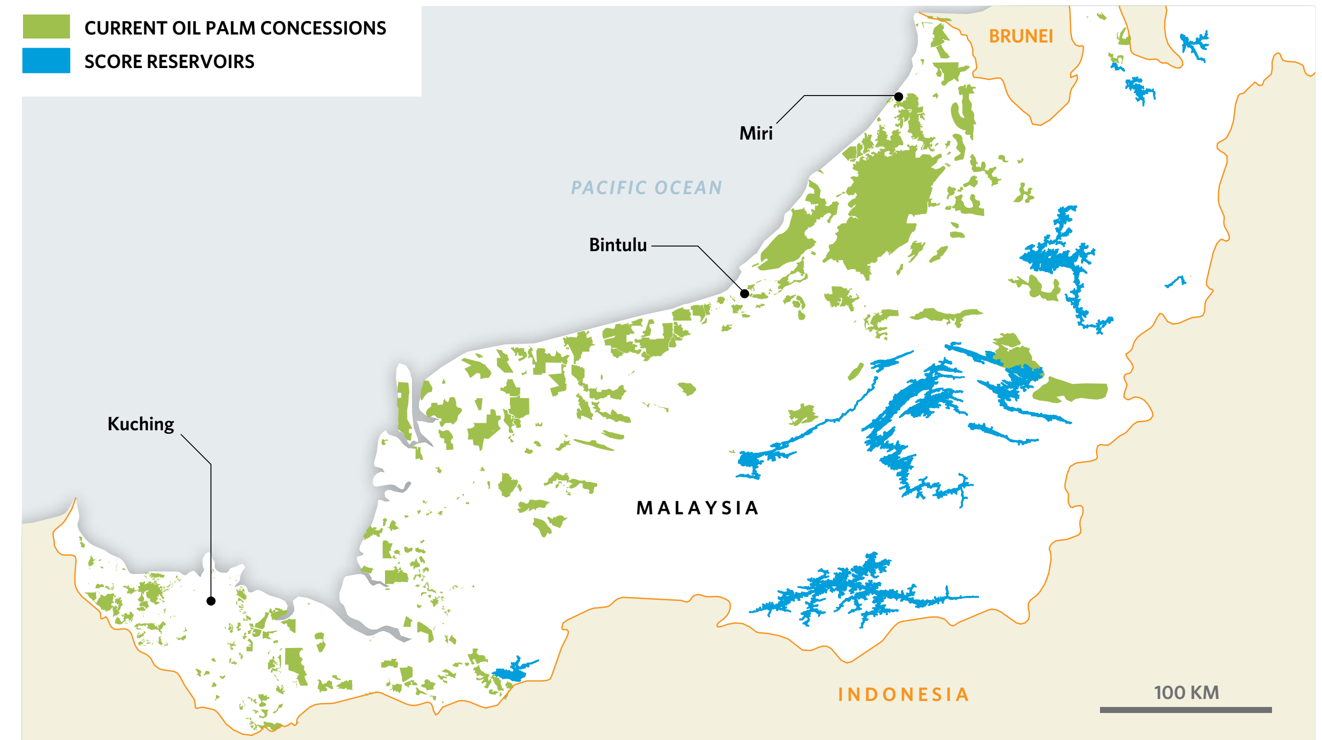
The oil palm industry in Sarawak represents a particularly high quality biomass waste resource. Sarawak alone represents 45 percent of Malaysian crude oil production with an average of 8.5 million tonnes annually. There are forty-one palm oil refineries across Sarawak and a number of these refineries are near major load areas allowing palm oil waste-to-energy to be a feasible option for energy production. The process of extracting crude oil and palm kernel from fresh fruit bunches (FFB) generates considerable amounts of residue. These include solid residues such as shells, fibers and empty fruit bunches (EFB), as well as liquid wastes including palm oil mill effluent (POME). A number of studies find the economics of oil palm waste to energy conversion to be feasible in Malaysia and Sarawak particularly.[108] Common energy conversion technologies explored for EFBs include ethanol production, methane recovery, compression and briquette production, and cogeneration or combined heat and power production. However, studies find that less than 30 percent of palm oil mills in Malaysia are involved in some sort of recycling activity for EFB or POME.[109] Thus, palm oil wastes represent a readily available resource in need of an innovative and efficient means of utilization.

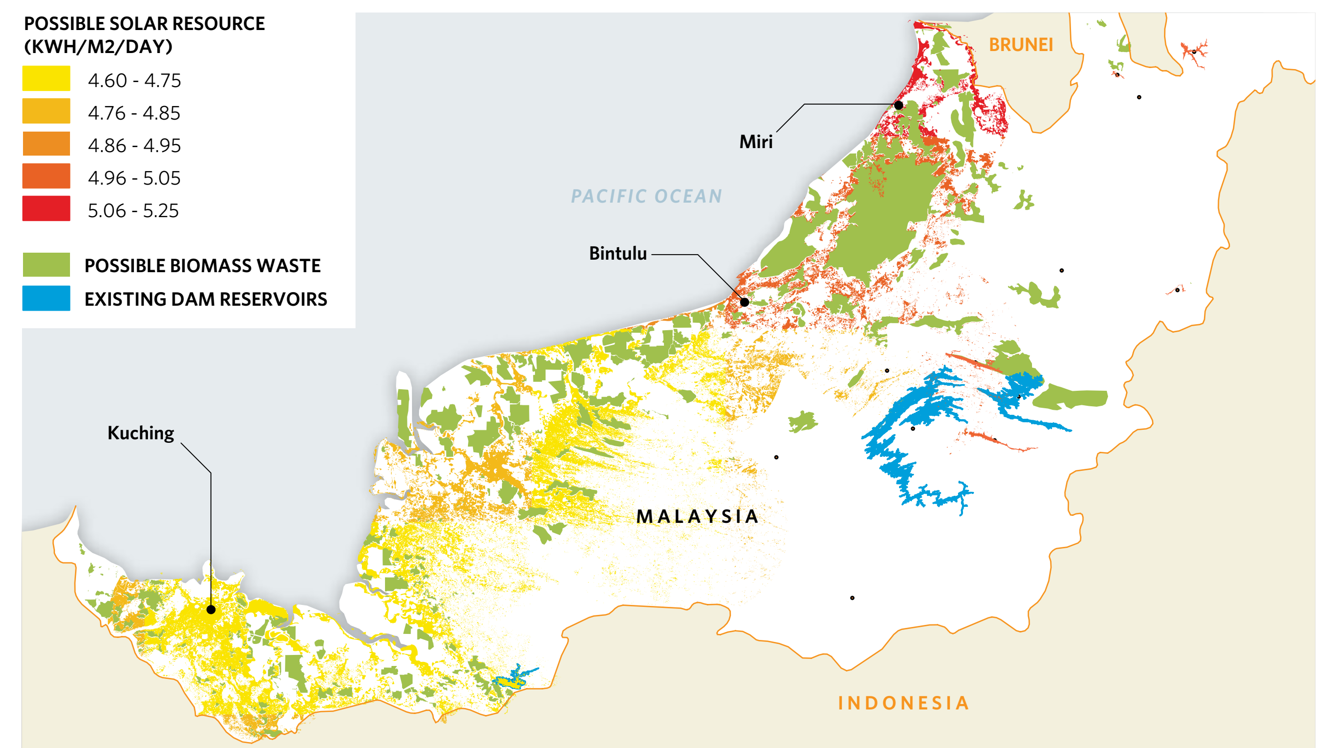
Further, Sarawak has considerable potential for solar energy (Figure 5.13). The minimum monthly average for insolation in Sarawak is found in the month of January at 3.26 kWh per square meter per day and maximum monthly value in April at 6.91 kWh per square meter per day with the annual average being 5.00 kWh per square meter per day. Though a good quality resource, according to the Malaysia Energy Commission, there are only 10 MW of photovoltaic capacity installed in Peninsula Malaysia through small SPPs ranging in size from 0.5 MW to 5 MW.[110] Thus there is also significant opportunity to develop the solar sector.

We estimate the size of the biomass waste resource from oil palm through correlation with total land area under palm oil plantation and standard yield rates. We estimate solar resource based on selection of zones that receive significant annual insolation (monthly averaged insolation above 5 kWh per m2 per day more than nine months of the year). Selecting only mill sites or solar resource within 50 kilometers of existing HV transmission and conservatively assuming only 3 percent of selected solar area can be used for PV, we find there is over 1 GW photovoltaic potential and 450 MW of biomass waste energy potential across the state, currently undeveloped. Future work will feature a more detailed study of the interactions between electricity sources, including how operations of existing hydropower facilities can support greater proportion of variable generation in the grid.

FIGURE 5.13

Spatial distribution of generation resources under different development scenarios. The top map shows distribution of reservoirs with hydropower development under the SCORE scenario. The lower map shows the distribution of decentralized generation sources (solar and POME).





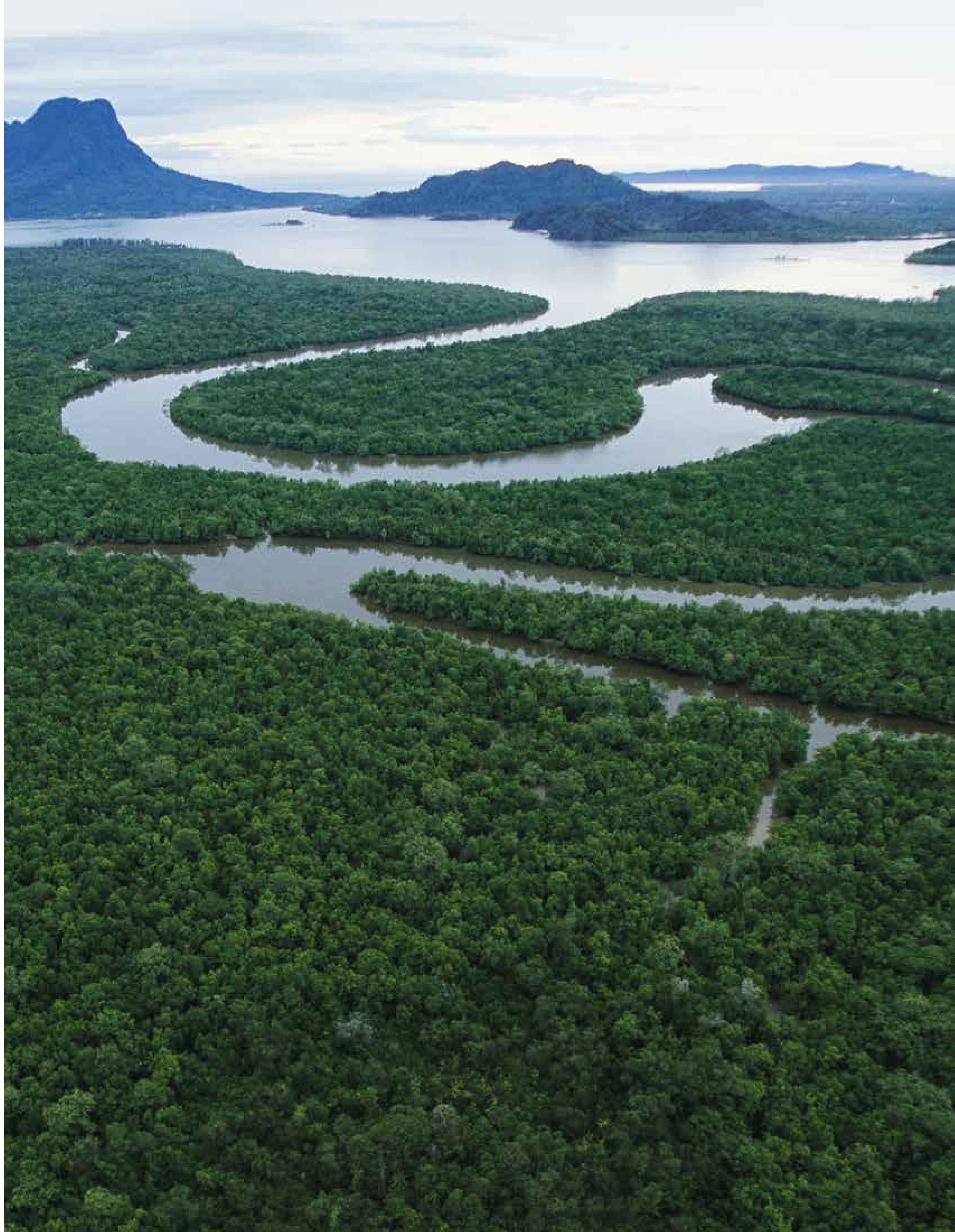
108 Bursa Malaysia Market, "Research Repository."
109 Chiew, et al., 2011
110 Suruhanjaya Tenaga (Malaysia Energy Commission), 2012.

Discussion: High-Level Energy System Planning Tools Can Reveal Sustainable Alternatives

Energy infrastructure is critical to the future of any rapidly developing economy. Unprecedented rates of growth in the global South have quickly raised the stakes for finding optimal energy technology mixes to keep pace with development needs, where the term “optimal’”usually derives from a techno-economic perspective. Yet the number of projects deployed in developing countries over the last two decades that perform poorly in terms of broader economic and environmental resources and public support, the environmental and public support, illustrates a major disconnect between planners, their tools and their project stakeholders.

Our application of a capacity-expansion methodology has implications for many other regions where the need for assessment of alternatives to large-scale energy infrastructure may exist. The Lower Mekong River Basin, for instance, is currently undergoing massive hydropower development (see case study earlier in this chapter). Similar large-scale energy infrastructure projects are underway across Africa and Latin America. These development pathways are often characterized by limited information, unrealistic assumptions of future demand and narrow definitions of cost (focused on technical and financial with oft-limited consideration of social and environmental costs) that impede broader evaluation of risk and tradeoff. In this case study, we demonstrated a simple and effective framework for assessing critical assumptions embedded in energy-infrastructure development strategy while also providing directionality for appropriate solutions.

Our results highlight that projections of future demand can be grossly overestimated, leading to unnecessarily high projections for needed growth in generation capacity. We also found that decentralized solar and biomass waste technologies can contribute significant capacity to the state’s energy portfolio and can meet realistic electricity demands at a lower financial cost than through development of additional large hydropower dams. These findings are consistent with other studies finding solar and biomass waste to be effective solutions for Borneo given their large resource potential.[111] The development pathways that include decentralized alternatives also would have dramatically lower impacts on indigenous communities, forests and rivers, although they also have higher emissions of GHG.



111 Shuit, et al., 2009; Sulaiman, et al., 2011.

Integrating Reservoir Operations and Floodplain Management: Yangtze, Mokelumne and Savannah River Basins[112]

A key principle of Hydropower by Design is the integration of other sectors and economic priorities within planning and management of hydropower. While most of the examples in this report of the integration of hydropower with water-management services focus on dam planning and operation, this system-scale integration can extend to land management as well, folding in interventions such as groundwater recharge or irrigation efficiencies. In these case studies we examine how management of floodplains can be integrated with the management of hydropower reservoirs to identify options that improve environmental, economic and financial performance of infrastructure within a river basin.

We summarize analyses within three different river basins that share a similar conceptual approach. The research focused on the potential to: one, reduce storage allocated to flood management within reservoirs; two, compensate for that reduced flood-management storage through interventions on the floodplain intended to maintain or improve flood safety for people, relative to the status quo; and, three, produce additional economic or environmental benefits with the increased storage made available by the reduction of flood storage in reservoirs. These economic benefits can include hydropower generation, water supply, or recreation. The environmental benefits include improved downstream flow regimes. Note that these analyses were conducted as proof-of-concept research. Changes to flood-management storage and operations are of course major decisions, and our presentation of these results does not imply endorsement from the relevant flood-management operators.

Yangtze River

In the Yangtze, we studied a cascade of hydropower dams and explored the potential for reducing flood storage in their reservoirs, coupled with investments in the downstream floodplain, to produce a broader mix of economic and environmental benefits, including addressing three important needs for the basin: one, flood-risk reduction; two, renewable energy generation; and, three, conservation and restoration of ecosystems and biodiversity.

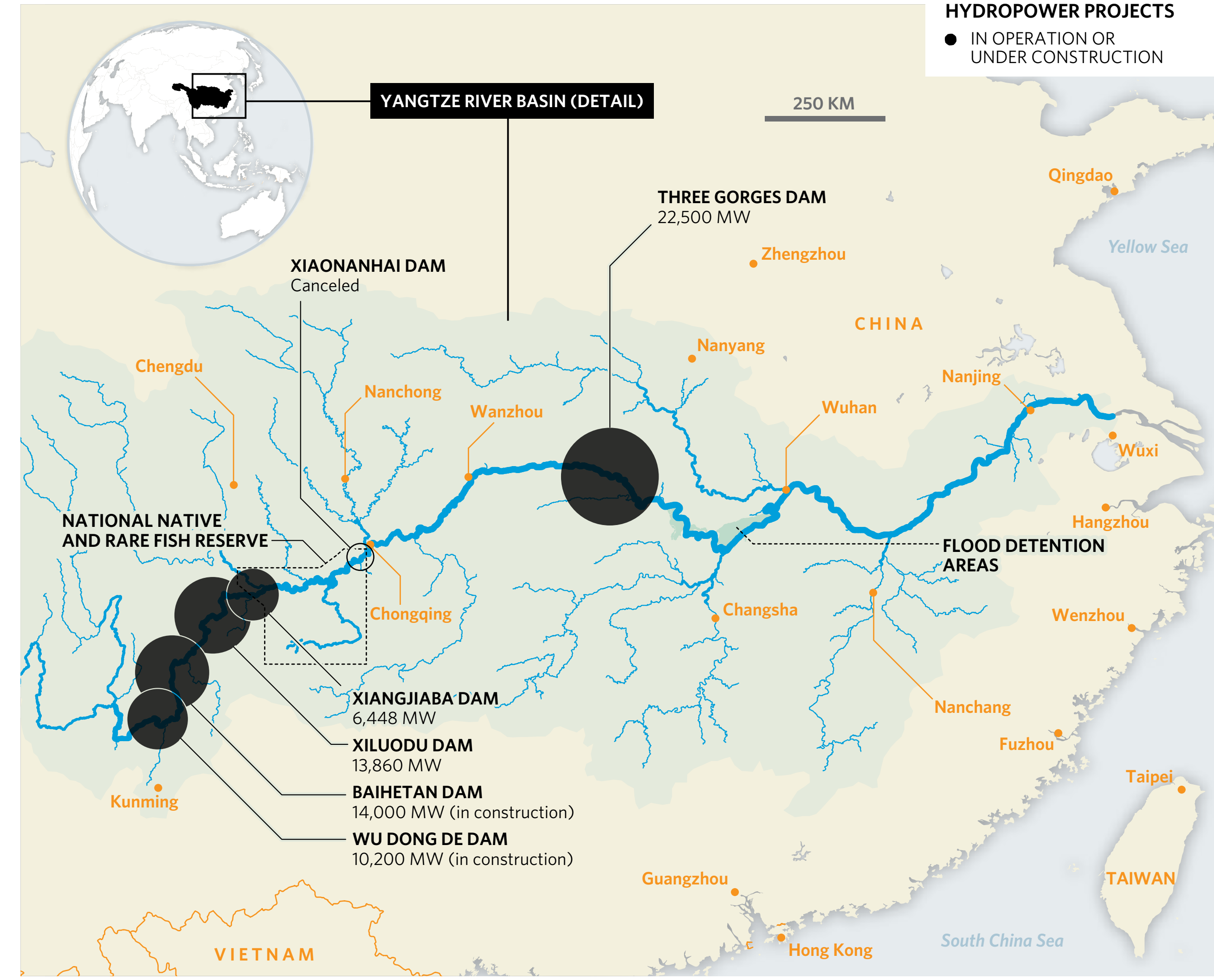
The Yangtze River basin supports a population of 400 million people and much of China's most productive agriculture. Flooding has been a major concern within the Yangtze valley for centuries. Although Three Gorges Dam has reduced flood risks, flooding remains an issue for the large populations and agricultural lands downstream of the dam (Figure 5.15). Future climate and hydrology models project that runoff and flood risk will increase in the Yangtze River basin due to increasing precipitation.[113]

The basin is also home to more than 170 endemic fish species, including ancient species such as the paddlefish and Chinese sturgeon. The Nature Conservancy identified many conservation priorities distributed throughout the basin,[114] including the National Rare and Native Fish Reserve, located upstream of the reservoir of Three Gorges Dam (Figure 5.14). This reserve is the last refuge for much of the Yangtze's unique aquatic species.

112 Key contributors: David Harrison, Qiaoyu Guo, Nathan Burley, Andrew Warner
113 Adam, et al., 2009.
114 Heiner, et al., 2011.

FIGURE 5.14

The Yangtze River Basin (China).



(YANGTZE RIVER IN CHONGQING, CHINA)

The China Three Gorges Project Corporation (CTGPC) is building a cascade of four large hydropower dams upstream of the Fish Reserve. These dams are also intended to provide flood control benefits by maintaining storage volume to attenuate floods. The Conservancy signed a memorandum of understanding with CTGPC to jointly develop recommendations for a flow regime out of the dam cascade that could maintain the viability of the Fish Reserve. The recommendations emphasized the conditions necessary to maintain fish reproduction. For example, for spawning, the four commercially important carp species require a rising hydrograph with water temperatures between 18 and 25°C. Initial analysis suggested that the cascade of dams would dramatically disrupt the flow regime and therefore severely degrade the viability of the Fish Reserve. To provide flood control, the reservoirs would be drawn down prior to the monsoon flood season, releasing a large pulse of water that was both too early in the year and too cold for the fish to spawn.

This reservoir drawdown would also reduce the hydraulic head of water passing through the turbines, thus reducing energy generation during the period of peak demand (the hot summer of Southeastern China). The Conservancy collaborated with Chinese research institutions on a series of feasibility studies that examine alternative reservoir operations, including an alternative that emphasizes managing flood risk in the downstream floodplain rather than in the four-dam cascade.

The feasibility studies include:

1. A comparison of various reservoir operation alternatives that ranged from the planned status quo (full flood-storage volumes) and partial reductions in flood-storage volume up to complete reduction (i.e., no flood storage). The research team examined the alternatives' energy generation and revenue and consistency with environmental flow objectives. Because changing these storage patterns would affect the pattern of flow available to pass through turbines, the team also examined increasing the turbine capacity within the cascade.
2. For each alternative, the team then examined flood hydrology and inundation patterns in the floodplain areas downstream of the four-dam cascade, including estimations of flood frequency and associated damages and costs.
3. The final analysis focused on potential strategies and associated costs to mitigate these flood risks through management actions in the downstream floodplain.

The downstream floodplain includes several "flood detention areas" (FDAs; Figure 5.14) which were designated as overflow areas by the Chinese government in the 1950s (similar to the Yolo Bypass of California's Central Valley). However, unlike the Yolo Bypass, these FDAs were settled and now have relatively large populations. Flood managers are reluctant to use the FDAs (they have essentially not been used), because doing so would incur high economic costs for evacuation, temporary housing and either resettlement or rebuilding following a flood. Failure to use the FDAs during a major flood greatly increases the risk for people living in the floodplain downstream of Three Gorges, including cities that could suffer catastrophic damages from levee failure.

The feasibility studies found that the four-dam cascade had a very minor influence on flood risk in the FDAs, in part because of the considerable regulation capacity of the intervening Three Gorges Dam and because the FDAs' aggregate flood risk includes flooding from rivers that originate downstream of both the four-dam cascade and Three Gorges Dam (i.e., floods for which neither Three Gorges Dam nor the new four-dam cascade can provide any flood-control benefit). However, reducing flood-storage capacity in the four-dam cascade could generate an additional US$350 to US$670M per year through increased hydropower generation, with the greater revenue possible with an increase in turbine size (Table 5.5). The Conservancy proposed that this additional annual revenue could be dedicated to a "Hydropower Sustainability Compensation Fund" that could support adaptation efforts by funding floodplain management improvements, emergency preparedness and an insurance program. The study concluded that investments by the Fund could result in improved flood safety for people and—by having a dedicated funding source—achieve these improvements much faster than under the current financial situation (no dedicated funds for improvements).

The Fund could reduce the current level of flood risk in the FDAs, including from floods that cannot be influenced by the four-dam cascade, by raising structures, making improvements to the FDAs' levees and providing safety areas for people. By reducing flood storage volumes in the upstream cascade and shifting greater flood-risk management onto the downstream floodplain, the Yangtze system could generate greater reservoir benefits (hydropower) and reduce flood risk across a wider range of flood levels and sources than could be provided by flood-control in the four-dam cascade. We estimate that hydropower generation could be improved by up to 10 percent and, due to the earlier investment in flood management improvements, improve flood-risk management by 26 percent over the next 35 years (see "reservoir and floodplain analysis" in Appendix E).

Further, the proposed alternative operation that would result from reducing flood-storage volume in the four-dam cascade would greatly diminish the hydrological alterations that would impact the Fish Reserve negatively. The cascade would be operated much closer to a run-of-river mode and provide a much more natural flow regime than the originally proposed operations. Thus, by integrating floodplain management with reservoir operations, the water-management system can provide a much better flow regime than could be produced by just working with the dams themselves.

This research was conducted at a proof-of-concept level and changing flood storage within reservoirs is a political challenge. However, the analysis does suggest that integrating reservoir reoperation and downstream floodplain management—linked by the funding made possible by the reoperation—has the potential to deliver broader benefits: one, lowered flood risk, achieved earlier; two, greater generation of renewable energy; and, three, improved environmental outcomes for river ecosystems and rare fish. The results of this research were used to advocate against building a dam, Xiaonanhai, within the Native Fish Reserve (Figure 5.15), as the analysis showed that reoperation of the already planned cascade could provide equal or more generation than Xiaonanhai, at lower investment cost and lower environmental impacts (Box 5.1).

TABLE 5.5

Energy generation and revenue (@ $0.0368/kwh) and environmental performance for three modeled operational scenarios for the four- dam cascade under construction on the upper Yangtze River. The additional revenue can be largely dedicated to improvements in downstream flood-risk management, reducing flood risk and achieving that reduction faster than would otherwise occur with status quo financial situation. In the two scenarios with no flood control storage, the percent time meeting environmental flow objectives varies depending on whether specific environmental flow operations are followed.

Scenario	Average annual generation (TWh)	Additional revenue above base case (million US$/year	Percent time achieving environmental flow objective
Base case – full flood control storage	190	--	49
No flood control storage	200	357	57 - 79
No flood control storage; 120 percent turbine capacity	208	667	57 - 79

BOX 5.1
Using Hydropower by Design to advocate for avoiding a damaging dam on the Yangtze

In 2011, the Chinese State Council voted to modify the boundaries of the Yangtze Native Fish Reserve to make way for construction of the Xiaonanhai Dam (Figure 5.14). The dam would have created a reservoir of hundreds of kilometers, converting a major portion of the Native Fish Reserve from a river—with the flowing water conditions required by the species the Reserve was intended to protect—into something more like a lake, with conditions that favor a range of generalist species. After that decision, the New York Times quoted the Conservancy's Guo Qiaoyu as saying, ""This is almost the last reserve for the whole river basin, especially after the construction of Three Gorges. [With Xiaonanhai] there will be very dramatic damage to these kinds of species."[115]

Several organizations advocated against the dam, emphasizing its environmental and social impacts. The Conservancy joined these arguments, highlighting research and recommendations of fish biologists that had been convened to develop environmental flow recommendations. But the Conservancy also argued against the dam from another angle, one made possible by the research on system-scale management options described in this case study. Xiaonanhai was designed with an capacity of 1.8 GW, undoubtedly a large dam for much of the world, but just a small fraction of the capacity of the downstream Three Gorges Dam (22 GW) and the combined capacity (42 GW) of the upstream cascade. The projected annual generation from Xiaoanhai would have been about 10 TW hours per year, or roughly the same as the incremental increase in generation from the "no flood control scenario" and half that of the "no flood control" with larger turbines. In other words, system-scale reoperation of a cascade already in development could provide as much or more generation as a new dam, with dramatically lower investment cost (Xiaoanhai would have cost more than US$5 billion) and dramatically lower environmental impact. For various reasons, largely political, the dam was suspended and then permanently removed from development consideration. The Native Fish Reserve is still a river.

Mokelumne and Savannah Rivers

The Nature Conservancy conducted similar studies on the potential benefits of reoperating multipurpose hydropower reservoirs in coordination with other sectors, such as flood-risk management, water supply, recreation and environmental conservation. These studies focused on the potential benefits of transferring flood-management functions from the reservoir to the downstream floodplain, such as through flood mitigation actions below dams, to enable a reduction of reservoir flood-storage space.[116] By liberating a portion of a reservoir's flood-control storage, the reservoir can provide greater benefits in the form of increased hydropower, enhanced water-supply reliability and environmental flows, with mitigation actions intended to maintain, or improve, flood safety.

This concept was explored in a set of feasibility studies examining coordination of multipurpose hydropower reservoir operations and floodplain management on the Mokelumne and Savannah rivers.[117] In the Mokelumne River (California, USA), the analysis focused on the reoperation of Camanche Reservoir, a multipurpose dam providing water supply, flood management and hydropower managed by the East Bay Municipal Utility District (Figure 5.15). For the Savannah River (Georgia and South Carolina, USA), the analysis focused on Thurmond Dam, managed by the U.S. Army Corps of Engineers to provide flood management along with hydropower, water supply and recreation (Figure 5.16).

In each of these systems, we modeled flood-storage volumes within reservoirs (ranging from 100 percent of current storage volume to complete elimination of reservoir flood storage) and then estimated the resulting changes to downstream flood inundation patterns and the production of benefits from the reservoir in terms of hydropower, water supply, recreation and the provision of environmental flows. For more details, see "reservoir and floodplain analysis" in Appendix E.

For the Mokelumne and Savannah, we compared the costs of the reservoir reallocation with the benefits (increased hydropower or water supply). Costs were summarized as either increased flood damages or the costs of changes in land use to mitigate for increased flood risk. For both rivers, we found that reducing flood storage to 50 percent of current volume would result in considerably higher total benefits from the system.

115 Wines, 2011.
116 The Nature Conservancy, 2012; Opperman, et al., 2009.
117 The Nature Conservancy, 2012.

FIGURE 5.15

The Mokelumne River Basin (California, USA)

HYDROPOWER PROJECTS
● EXISTING HYDROPOWER DAM

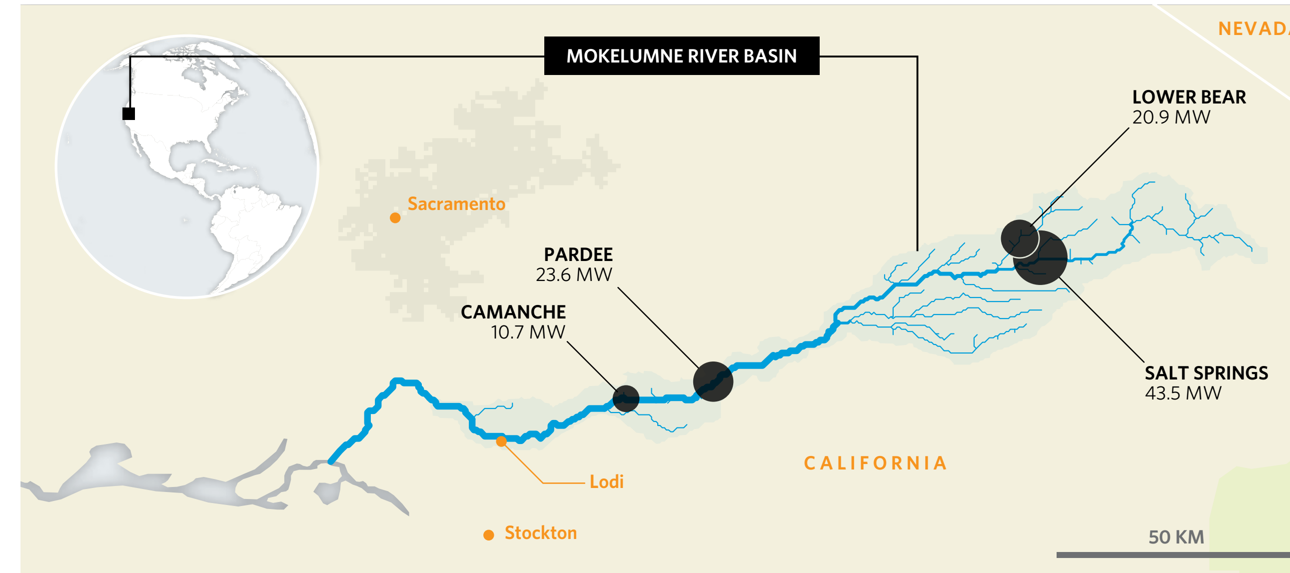
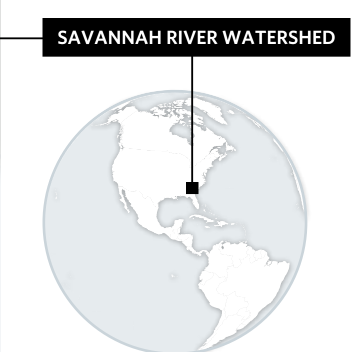


FIGURE 5.16

The Savannah River Basin (Georgia and South Carolina, USA).

HYDROPOWER PROJECTS
● EXISTING HYDROPOWER DAM



© MARK GODFREY/THE NATURE CONSERVANCY (SAVANNAH RIVER, AUGUSTA, SOUTH CAROLINA, USA)

Coordinated reoperation on the Mokelumne would produce a net economic gain (US$2.1 million per year), primarily due to benefits for water supply. Hydropower revenue would increase by approximately US$200,000 per year. In addition, the change in reservoir storage patterns in the Mokelumne would allow the reservoir to meet environmental flow releases for salmon four times more frequently (Table 5.6)

For the Savannah, this change in operations would yield net marginal annual benefits of nearly US$13 million per year, largely due to a 10 percent increase in hydropower generation (Figure 5.17). The reoperation would also: one, decrease by 55 days the average numbers of days per year where the reservoir levels were below designated drought levels (a 20 percent improvement); two, improve recreation during the summer (worth US$3 million per year); and, three, result in four-fold increase in the frequency with which ecological flood recommendations could be met. The reoperation would increase annualized flood damages by US$588,000, which could largely be mitigated by the buyout of a set of properties that are already at risk of flooding.

FIGURE 5.17

Average annual costs and benefits of reservoir reoperation of the multipurpose hydropower dam on the Savannah River (GA, USA).

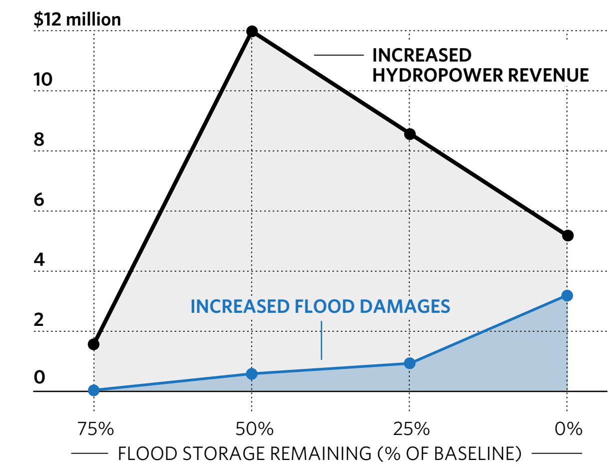


TABLE 5.6

Average annual hydropower generation, urban water supply shortage costs, and percent of years in which a spring pulse flow for salmon outmigration can be achieved from Camanche Dam on the Mokelumne River.

Scenario based on volume of flood storage (% of full storage)	Hydropower Generation (average MWh/year)	Urban water supply shortage cost (average $/year)	Percent of years with a spring pulse flow
100%	43,400	10,754,000	14.6%
75%	46,200	10,754,000	26.8%
50%	47,700	9,511,000	47.6%

Blue Nile[118]

Basin Overview

The Blue Nile is the largest tributary of the longest river in the world, the Nile. It originates in the Ethiopian highlands and flows towards Sudan's capital Khartoum (Figure 5.18). The river's flow has great variability, both seasonally and between years. It contributes more than half of the Nile volume reaching Egypt.

The Blue Nile has large potential for hydropower with identified sites in Ethiopia that could generate up to 40 TWh per year. Although potential sites were identified in the 1960's[119] and hydropower dams have been built on the Blue Nile in Sudan, until recently little development has occurred in the Ethiopian reach of the Blue Nile.

Regulation of the river by reservoirs in the Ethiopian part of the Blue Nile basin could potentially reduce impacts from floods in Sudan and enhance low flows. However, downstream countries are concerned that the filling of the reservoirs will negatively impact water availability (e.g., for irrigation) and performance of downstream hydropower reservoirs in Sudan and Egypt.[120]

The environmental and downstream economic impacts of proposed Blue Nile dams and their financial costs and benefits will depend on the size, sequence of implementation and operating policies of the reservoirs. Hence, an analysis of investment options (sequence, design and operation of dams) and tradeoffs involved in these choices could inform this discussion and potentially identify development options that stakeholders find acceptable. Table 5.7 shows six proposed dams of the Blue Nile. This case study examines the mixes of benefits attainable if two, three or four of these were implemented. Only a maximum of four reservoirs can be implemented among the six identified, because some of the reservoirs will inundate the dam sites of others.

BLUE NILE RIVER BASIN

Location: Ethiopia, Sudan

Basin type: future development, water scarce

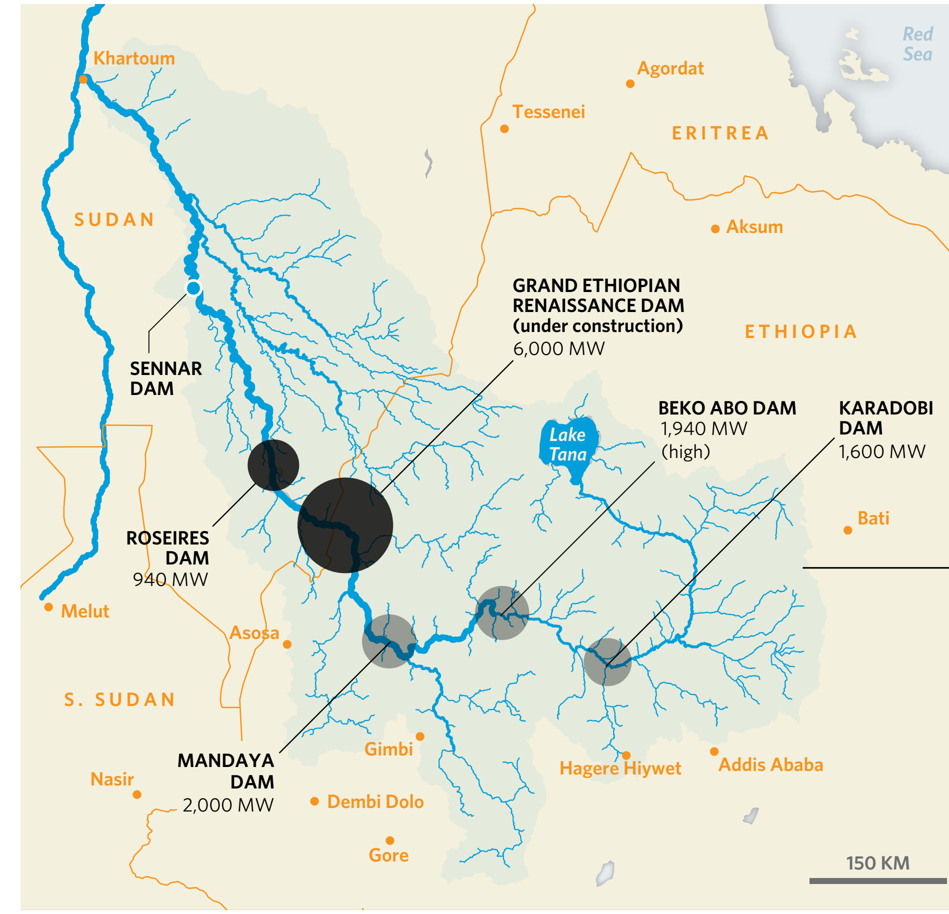
Basin size: 310,000 km^2

Basin population: 31,000,000

Mean annual flow: 1,560 cms

Resources considered in case study: hydropower, environmental flows, downstream flows during filling (irrigation)

Key result: HbD options offered a range of improvements for environmental flows or to the downstream flow during reservoir filling, for similar generation, compared to the BaU option. Flows during reservoir filling are an important consideration for downstream irrigation and for addressing concerns of downstream riparian countries.



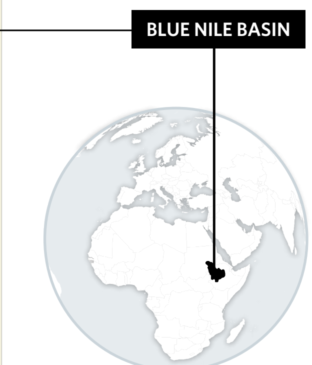


FIGURE 5.18

The Blue Nile river basin in Ethiopia and Sudan.

TABLE 5.7
Potential and under construction dams on the Blue Nile in Ethiopia.

Dam	Mutually exclusive with	MaxStorage (MCM)	Installed Capacity (MW)
Beko Abo High	Karadobi, BekoAboLow	31,692	1,940
Beko Abo Low	BekoAboHigh	1,751	935
GERD	Mandaya	72,000	6,000
Karadobi	BekoAboHigh	40,200	1,600
Mandaya	GERD, UpperMandaya	48,088	2,000
Upper Mandaya	Mandaya	27,702	1,700

118 Lead researchers: Robel Geressu and Julien Harou.
119 Whittington & McClelland, 1992; Arsano & Tamrat, 2005; Cascão, 2008; Hefny & El-Din Amer, 2005; Wheeler et al. 2016.
120 Abdelhaleem & Helal, 2015; Whittington, et al., 2014.

Analysis: Blue Nile multi-reservoir system design problem

This case study examines decisions about infrastructure investment and operations, including the number, location and type of new dams and their operating rules. We examine a Hydropower by Design (HbD) approach and compare it to a Business as Usual (BaU) case. For the BaU approach, each individual reservoir's operating rules are optimized solely to maximize its own energy generation. Operating rules are first optimized for a three-year filling period, then for regular operation after filling. The sequence of BaU reservoir investments is optimized, assuming five years between each activation.

The HbD approach makes decisions that optimize system-level performance for a set of metrics: maximizing energy generation, minimizing flow alteration, maximizing the downstream flow during reservoir filling and maximizing the net present value of hydropower investments. Both operations and sequencing of reservoirs are optimized to all objectives simultaneously (resulting in tradeoffs – see Figure 5.20 below). Furthermore, each reservoir's operating rules are not optimized in isolation for a filling period and a full-reservoir period, but rather as the system gradually expands with reservoirs filling then becoming full, the operating rules are regularly re-optimized to reflect the new reality (as new reservoirs are activated).

This approach reflects the value that can be attained when multi-reservoir systems designs consider how the operating rules of downstream reservoirs could be changed to best adapt to changes in the hydrograph from upstream development. The optimization algorithm also considers the mutual exclusivity of projects. Operating rules were formulated as storage vs. release curves for each reservoir.[121]

The net present value of investment options is computed by first discounting the future energy production value (US$0.08 per KWh times the energy generation of new reservoirs estimated monthly over a 100-year period). Then the discounted capital costs of the dams are subtracted from the future energy production value.

Although the Blue Nile downstream of Ethiopia is regulated by hydropower dams in Sudan, we included an environmental flow metric in this proof-of-concept application to illustrate tradeoffs and opportunities between generation and environmental flows from a cascade. Accounting for Gao, et al.'s,[122] eco-surplus and eco-deficit approach, we used a flow alteration metric which assesses the deviation of the regulated flow from the unregulated flow frequency curve. The flow alteration is used as a general indicator of downstream environmental conditions (e.g., less alteration is associated with improved environmental performance). For more details see "tradeoff analysis" in Appendix E.

Results

In Figure 5.19, Panels 1 and 2 show modeled average annual generation and the tradeoffs with the downstream flow during filling period of reservoirs and flow alteration metric respectively. Panels 3 and 4 show the present net value estimate of the proposed Blue Nile multi-reservoir system and the tradeoffs with downstream flow during filling periods and the flow alteration metric.

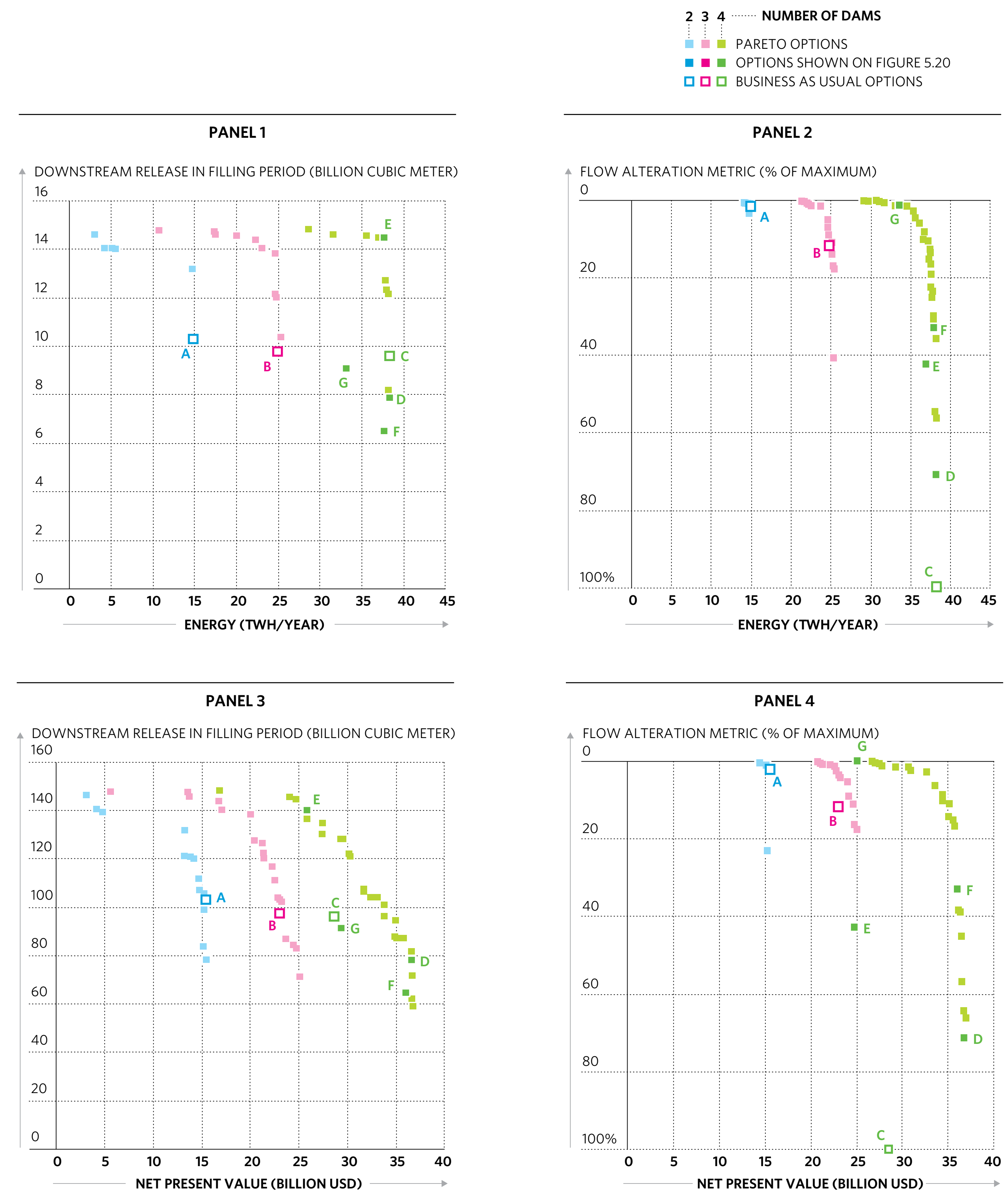
Visualizing the tradeoff plots provides insights into where stakeholders with one primary interest (e.g., maximizing energy generation) might find compromise solutions more acceptable than others. The tradeoff plots show the marginal cost (in terms of one or more performance metric) for improving a different performance metric. For example, in Panel 2, the flow alteration metric can be reduced substantially moving from 'D' to 'F' with relatively small sacrifice (opportunity cost) in annual energy generation compared to moving from 'F' to 'G'.

Overall results show an HbD approach improves performance over the BaU approach in several dimensions simultaneously. A BaU design which aims to optimize only energy generation would identify multi-reservoir designs 'A', 'B' and 'C' (i.e., for two, three and four reservoirs respectively). Ignoring the performance gains from coordinating operating rules of the reservoirs in the multi-reservoir setting could lead to a missed opportunity to enhance system performance (e.g., in Panel 4 selecting BaU option 'C' misses gains in both NPV and environment that are available with option 'D').

121 Geressu and Harou, 2015.
122 Gao, et al., 2009

FIGURE 5.19

Two-dimensional tradeoff plots showing the comparison of performance under BaU and HbD options. Each point on the scatter plot represents a combination of proposed reservoirs and their operating rules. Combinations with different numbers of dams (2, 3, or 4) are denoted by different colors and BaU options are denoted by hollow markers.

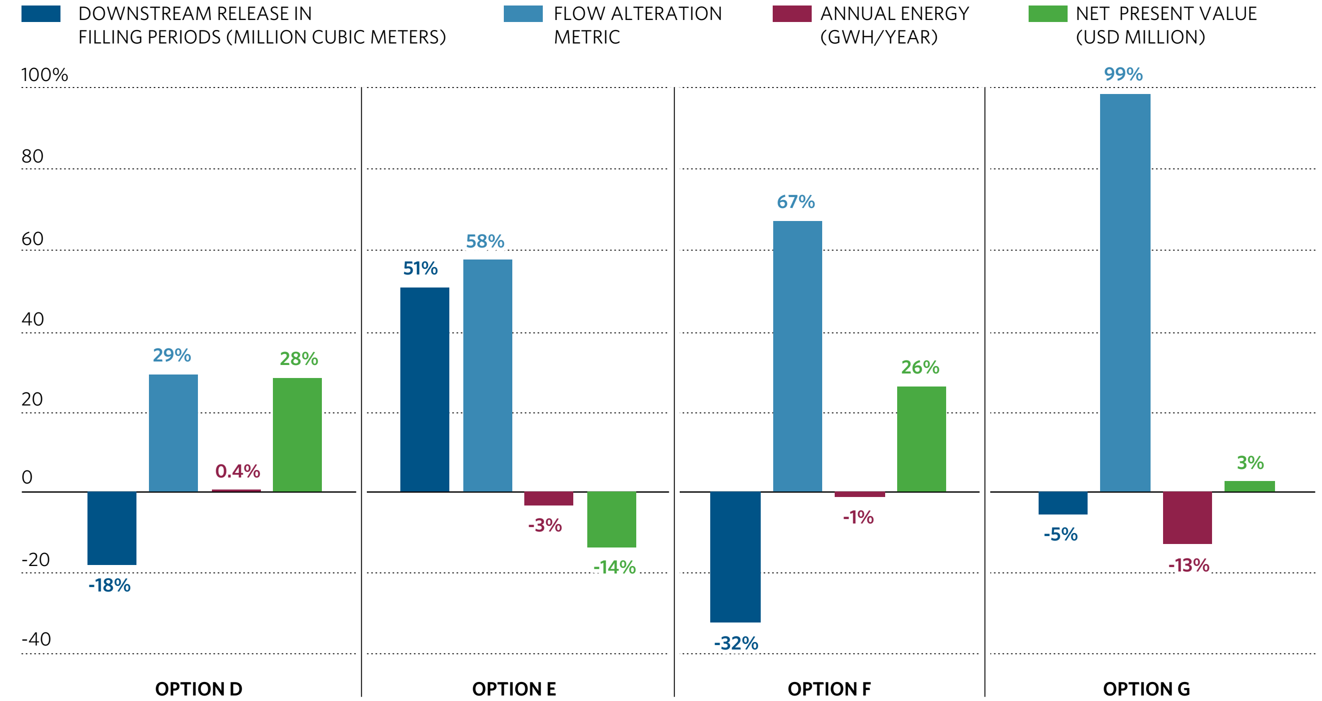


© BRUCE KIRKBY (BLUE NILE GORGE, ETHIOPIA)

FIGURE 5.20

Performance comparison for selected four-dam HbD options, relative to BaU (option C in Figure 5.19). Note that "positive" bars indicate improved performance, so a positive bar for flow alteration metric indicates reduced flow alteration.

PERFORMANCE RELATIVE TO "BUSINESS AS USUAL"



Conclusions

We searched for hydropower options that perform better across several metrics compared to options that only optimize energy generation for each single dam (BaU). The study showed that HbD can lead to large gains in system performance (energy generation, financial, environmental, downstream release during filling) compared to BaU at various levels of development (system expansion ranging from two to four new dams).

In this case, HbD options allowed increasing the net present worth of benefits up to 5 percent and improving the flow alteration metric by up to 100 percent. The HbD analysis approach also reveals where relatively small sacrifices in the primary performance objective (e.g., reduction of annual energy generation by less than 1 percent) could lead to up to 67 percent improvement in the environmental (flow alteration) metric (Figure 5.20).

Overall, the results for this particular application on the Blue Nile indicate that HbD could identify alternative options where relatively small compromises in generation could lead to considerable increases in other measures of system performance—and thus considerable improvements in the way hydropower systems share benefits. By highlighting the potential for shared benefits, decision makers may be able to justify permitting options with small reductions in energy or financial benefits in order to gain considerable increases in environmental performance and/or reductions in negative downstream impacts.

Disclaimer: This is a proof-of-concept study on a subset of the decision challenges confronting infrastructure development and water management on the Nile, based on a limited set of potential planning and management objectives. Expanding this work would require a water resources model of the whole Eastern Nile Basin to explore how the management of different upstream options would impact downstream energy and irrigation systems in Sudan and Egypt. Other issues for the Nile stakeholders include, but are not limited to, the management of the reservoir system under drought and flood conditions and how the benefits and costs of new investments could be shared to build greater consensus among the Nile riparian countries.

Myitnge[123]

Basin Overview

Myanmar's Myitnge River (also known as the Dokhtawaddy) is a tributary of the Irrawaddy, entering the river just south of Mandalay (Figure 5.21). The main river is contained within a gorge through much of its length, flowing through a basin that is forested with high biodiversity value. The Irrawaddy south of the confluence flows through Myanmar's dry zone, so low flows are important for maintaining navigation and irrigation.

The basin contains one operational hydropower dam—the Yeywa—and one hydropower dam currently under construction—the Upper Yeywa. Three other potential hydropower sites exist (Table 5.8). The generation potential of this dam inventory indicates that potential plans are to increase generation in the basin up to approximately 4.5 TWh per year. However, Hsipaw dam would involve considerable displacement of local people, so we investigated options for generating close to this level without building that dam. Therefore, we examined the generation potential from adding two dams, in locations that would have minimal displacement and also minimize additional river fragmentation because they are located within, or just below, the existing cascade. The BaU option modeled operations of the dams (existing and new) to maximize their individual generation, whereas the HbD options modeled operating the four dams as a system. For more details see "tradeoff analysis" in Appendix E.

MYITNGE RIVER BASIN

Location: Myanamar

Basin type: future development, water scarce

Basin size: 47,000 km^2

Basin population: 4,000,000

Mean annual flow: 723 cms

Resources considered in case study:
hydropower, fish productivity, navigation, irrigation, flood management

Key result: A HbD scenario could increase firm generation by 6 percent and increase low flows to support downstream irrigation and navigation by nearly 25 percent, compared to the BaU option.

TABLE 5.8

Existing and potential hydropower dams in the Myitnge basin.

Dam name	Status	Capacity (MW)	Inundated area (km^2)
Yeywa	Existing	790	95
Upper Yeywa	Under Construction	308	267
Deedoke	Potential	60	11
Middle Yeywa	Potential	150	7 – 21[124]
Hsipaw	Potential	100	50

123 Lead researchers: Anthony Hurford and Julien Harou. For more information on the Myitnge and the modeling for tradeoff analyses for the basin, please see the 2016 report from The Nature Conservancy, WWF, and University of Manchester, funded by the UK's Department for International Development.
124 Different dam heights are under consideration which would result different inundated areas

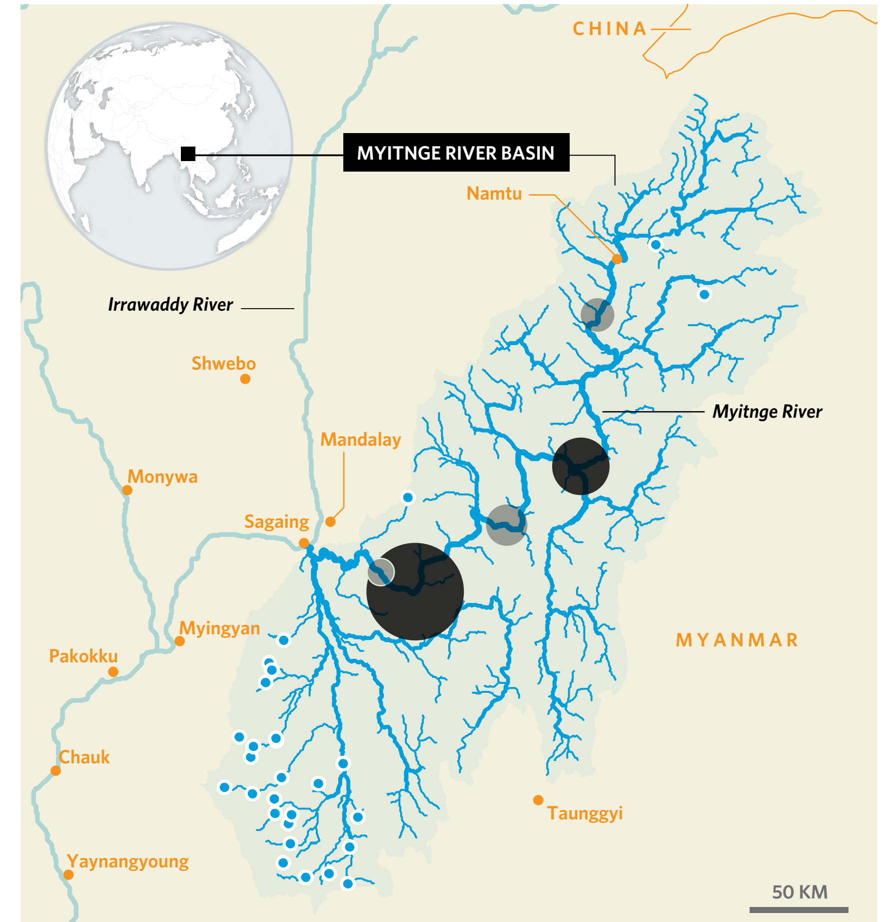


FIGURE 5.21
The Myitnge River basin, a tributary to the Irrawaddy in Myanmar.

HYDROPOWER PROJECTS
- EXISTING HYDROPOWER DAM
- POTENTIAL DAM SITE
- NON-HYDROPOWER DAM

750 MEGAWATTS
500
250
100

We compared performance of BaU and HbD options across three performance metrics:

Annual generation: Average GWh generated each year over the 20 years of simulation. This metric was maximized.

Firm generation: Monthly generation achieved with 90 percent reliability over the 20 years of simulation. This metric was maximized.

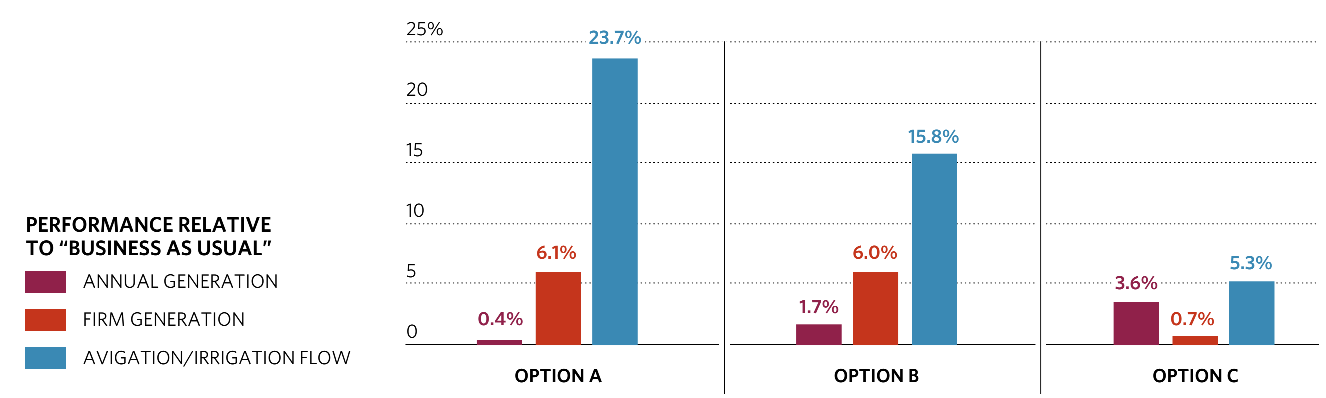
Irrigation and navigation flow: Low flows at the basin outlet contribute to downstream irrigation and river navigation needs in the Irrawaddy during the dry season. This metric was maximized.

Trade-off analysis results

The multi-criteria search identified three HbD options to compare to BaU baseline performance (Figure 5.23).

Because the BaU and HbD options include the same selection of dams, benefits can only vary as a function of dam operations. The three HbD options all have higher annual generation than the BaU option. However, increasing generation comes at a cost in performance of other metrics. As annual generation increases from option A to option C, firm generation and low flows for navigation and irrigation both decline (Figure 5.22). The navigation and irrigation flows appear to be correlated to firm energy because releasing water consistently through the turbines to provide firm energy also provides more consistent low flows than releases to maximize generation on an annual basis. In this model, fishery production was related to connectivity and sediment (nutrient availability)[125] and that did not vary between the options. Thus, the options were all equivalent for fishery production. Overall however, the three HbD options performed better than the BaU option across the metrics. The tradeoff analysis indicates that decision makers and managers could select among a range of distribution among the additional benefits.

FIGURE 5.22
The performance of HbD alternatives relative to the business as usual (BaU) option on the Myitnge River, in terms of three performance metrics. All three Options and the BaU case build the same dams (Deedoke and Low Middle Yeywa), but Hydropower by Design identifies operating rules which allow the dams to perform as a system to achieve higher performance. Note that fishery performance was modeled, but did not vary between options, so it is not visible in this figure.



125 The Nature Conservancy, et al., 2016.

Penobscot

The Penobscot River basin (22.3 million hectares) is the largest in Maine and second largest in the Northeastern United States (Figure 5.23). Archeological evidence indicates that the Wabanaki people—four tribes that include the present-day Penobscot—began living in the Penobscot River valley at least 9,000 years ago and continuously occupied the region through pre-contact times.[126] Fish from the Penobscot were a primary source of food for the Penobscot Indian Nation. Following European settlement, migratory fish that used the Penobscot—including Atlantic salmon and American shad—supported a large commercial fishing industry.

Starting in the 1820s and 1830s, dams were constructed on the Penobscot mainstem and impacts to migratory fish became apparent the first year after the closure of Veazie dam: "a great many shad and alewives lingered about the dam and died there, until the air was loaded with the stench."[127] About a century later, the Penobscot River run of Atlantic salmon was added to the list of endangered species, under the Endangered Species Act. The listing reflected more than a century of dramatic declines in salmon and other migratory fish, leaving a legacy of significant cultural and economic impacts on the Penobscot Indian Nation and local communities.

Dams on the Penobscot—and nearly all non-federal hydropower dams in the United States—are regulated by the Federal Energy Regulatory Commission (FERC), created by the Federal Power Act.[128] FERC issues 30- to 50-year licenses to hydropower projects. Projects must undergo a relicensing process prior to license expiration. An amendment to the Federal Power Act—the Electric Consumers Protection Act of 1986 (ECPA)—required FERC to give "equal consideration" to conservation and recreational uses of rivers alongside hydropower production. Through ECPA, Congress directed FERC to provide a greater balance within licensing processes between energy production and recreational and environmental resources.[129] Through this change, relicensing became an opportunity to update projects' environmental and social performance and to reconsider the balance between energy generation and other benefits from rivers. This change also gave expanded influence to several state and federal agencies as well as Native American tribes. Conservation organizations also increased their ability to engage with, and influence, relicensing processes.

PENOBSCOT RIVER BASIN

Location: Maine (USA)

Basin type: current development, water abundant

Basin size: 23,400 km^2

Basin population: 220,000

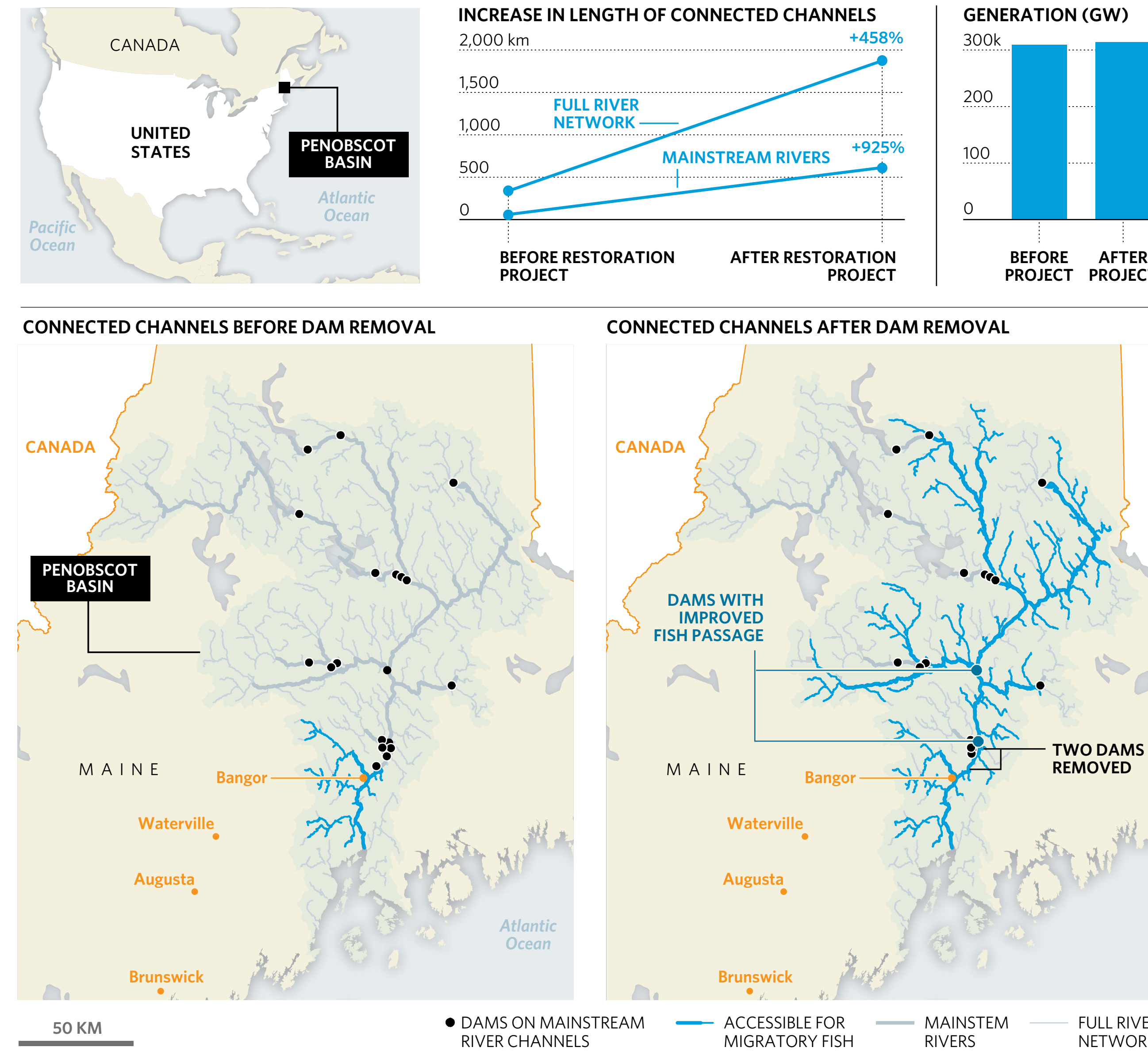
Mean annual flow: 342 cms

Resources considered in case study: hydropower, migratory fish habitat

Key result: A system-scale plan resulted in the removal of two dams, and a third was bypassed, allowing access to 1000 additional kilometers of river and stream habitat for migratory fish. Due to equipment and operational changes at existing dams, total generation from the basin will increase somewhat.

FIGURE 5.23

The Penobscot River (Maine, USA) and generation for hydropower and length of river channel accessible to migratory fish, before and after dam removal.



126 Sanger, et al., 1992.
127 Foster and Atkins, 1869.
128 Federal Power Act, 16 U.S.C. §§ 791a-825.
129 Gillilan and Brown, 1997.

In the twentieth century, after decades of contentious licensing processes for individual dams had failed to resolve conflicts on the Penobscot between energy generation and migratory fish passage. Early in the new century, a single hydropower company, PPL Corporation, acquired the major dams on the Penobscot mainstem, providing an opportunity for a broader solution. A diverse set of parties discussed and negotiated the major energy and conservation issues, including PPL Corporation, the Penobscot Indian Nation, the state of Maine, the Department of the Interior (Bureau of Indian Affairs, US Fish and Wildlife Service, National Park Service) and five non-profit conservation organizations (American Rivers, Atlantic Salmon Federation, Maine Audubon, Natural Resources Council of Maine and Trout Unlimited). In October 2003, the parties announced that they had reached a conceptual agreement that outlined the principles for rebalancing fisheries restoration and hydropower production on the lower river. In 2004, the parties filed with FERC the Lower Penobscot River Comprehensive Settlement Accord, a multiparty legal agreement designed to reconfigure hydropower production on the lower Penobscot system to both restore migratory fish populations while maintaining hydropower production under new licenses at PPL's dams. Under the agreement, PPL granted a five-year option to purchase three dams (Veazie, Great Works and Howland) to the newly created not-for-profit Penobscot River Restoration Trust ('the Trust') for between US$24 million and US$26 million. The Trust is composed of the Penobscot Indian Nation and the five conservation NGOs involved in the negotiation. The Nature Conservancy joined the Trust as a sixth conservation NGO in 2006.

Since then, Veazie and Great Works dams have been removed (Figure 4.4) and the power plant at Howland has been decommissioned. While the Howland dam remains (the community preferred to maintain current river levels above the dam), a nature-like fish bypass that looks much like a stream has been constructed around the dam (see photo). The bypass fishway at Howland can accommodate a broad range of flow conditions and its slope (1.5 percent) is sufficiently low such that relatively poor-swimming species, like American shad, can use it to reach upstream spawning habitat (Figure 5.24). PPL also committed to improving fish passage at other remaining dams in the basin.

Based on the increase in connected habitat for migratory fish, biologists estimate that fish populations using the basin will increase dramatically, with projections that Atlantic salmon will increase from a few thousand to 12,000 and shad will increase from a few thousand to over 2 million.[130] Dam removals and fish bypass construction occurred between 2013 and 2016 and the response of some fish populations will show a lag of several years after the changes. Some fish populations have already showed a rapid response, however, with river herring numbers reaching nearly 600,000 in 2015[131] and 1.8 million in 2016, an increase of 135 times the level before the dam removals.

Due to the challenges of measuring fish populations, in this report we focus on a proxy for migratory fish populations: their migratory habitat, measured in kilometers of river and stream channel accessible to migratory fish. In the case of the Penobscot, this means the length of the channel network accessible to fish moving upstream from the ocean. Following the restoration project—dam removal, fish bypass and fish passage at one remaining mainstem dam—the accessible network of large river and stream channels will increase from 60 kilometers to 615 kilometers, an increase of 925 percent. Some fish use smaller stream channels for spawning; considering that larger network of smaller channels, the accessible network will increase from 340 kilometers to 1,880 kilometers, an increase of 450 percent (Figure 5.23).[132]

FIGURE 5.24

© JOSH ROYTE/TNC (HOWLAND DAM, PENOBSCOT RIVER, MAINE)

In addition to these dramatic increases in fish and fish habitat, the agreement will maintain energy generation from the Penobscot. Under the Accord, PPL received new licenses for their remaining six dams in the Penobscot basin, including the right to increase hydropower generation at these dams to maintain total basin energy generation at current levels (Figure 5.23). The project-level increases in generation will be achieved through re-powering Orono Dam (on the Stillwater Branch of the Penobscot, which is parallel to the main channel), adding an additional foot of head on three impoundments and taking turbines from decommissioned dams and installing them in four other PPL system dams. Due to these improvements, PPL Corporation projects a slight increase in energy generation after project completion.[133]

The project was strongly influenced by the licensing requirements for hydropower projects in the United States. From the perspective of the private sector participant in this case study (PPL), the financial business was primarily related to regulatory compliance.

PPL was compensated for selling the three dams to the restoration program. Along with the dam purchases, the costs for planning and implementing the project required an investment of approximately US$50 million, largely from public sources. An economic analysis of the project indicates that it will produce net economic gains for the region in terms of commercial fishing, recreational fishing and other recreational values.[134] Further, the project produced outcomes that have been long sought by the Penobscot Indian Nation, allowing some restoration of cultural traditions and resource access.

A modeling study for the Willamette River basin (Oregon, USA) concluded that similarly dramatic increases in migratory fish habitat were possible with minimal losses of generation or water storage. Kuby, et al., assessed strategies to increase the amount of connected channel network for salmon in Oregon's Willamette River basin and assessed tradeoffs with various removal options from among 150 dams in the basin. They found that removing only 12 dams could reconnect 52 percent of the drainage basin with a loss of less than 2 percent of the basin's hydropower and water-storage capacity.[135] Storage in the Willamette is dominated by flood-risk management storage. Based on their calculations, removal of the 12 dams would increase the drainage area of the Willamette connected to the ocean from 2,950 square kilometers to 16,814 square kilometers, an increase of 470 percent. Note that, although they used drainage area, length of channel will be highly correlated to drainage area. The study suggests that dramatic increases in the length of river and stream kilometers accessible to migratory fish could be achieved with extremely small losses of the primary benefits of dams: generation and flood-risk management. This analysis was a proof-of-concept study. Similar to the Penobscot, implementation would likely hinge on strong regulatory drivers and investment of public funds, targeted to achieving net regional economic gains. Mitigation banking (discussed in Chapter 6) could potentially serve as a market-based catalyst to increase the likelihood of river restoration projects similar to Penobscot or what was modeled for the Willamette.

130 Opperman, et al., 2011a; Opperman, et al., 2011b.
131 Miller, 2015.
132 See case study for methods and discussion for how fish passage was

133 Finally, the Accord provides PPL with new licenses for their remaining six dams in the Penobscot basin, including the right to increase hydropower generation at these dams to maintain total basin energy generation at current levels (Figure 4). The project-level increases in generation will be achieved through re-powering Orono Dam (on the Stillwater Branch of the Penobscot, which is parallel to the main channel; Figure 1), adding an additional foot of head on three impoundments and taking turbines from decommissioned dams and installing them in four other PPL system dams (Table 2). Due to these improvements, PPL Corporation projects a slight increase in energy production after project completion (PPL Corp, pers. comm. Scott Hall, 2008)
134 NOAA, 2010.
135 Kuby, et al., 2005.

Tana[136]

Basin Overview

The Tana river drains the slopes of Mount Kenya and the Aberdare Mountains and flows approximately 1,000 kilometers to the Indian Ocean (Figure 5.25). The upper basin features steep slopes that receive high mean annual rainfall (nearly 2,000 millimeters annually) and prime agricultural land, much of it planted in export crops. The Nature Conservancy and partners (including KenGen, the country's largest electricity producer) have developed a "water fund" in the upper Tana basin to restore riparian areas and improve agricultural practices to reduce sediment input into the hydropower cascade and drinking water sources.[137]

In the lower basin, the terrain flattens into semi-arid plains with dramatically less rainfall (only 305 millimeters annually). In this dry region, the Tana is flanked by riverine forests that provide habitat to species with high value for ecotourism, including endemic and endangered primates and an antelope (the hirola). The river terminates in a delta at the Indian Ocean. Along the lower river and delta, people graze cattle in floodplain grasslands, practice flood-recession agriculture and catch fish in both freshwater and near-shore habitats. All of these services are highly influenced by flood flows in the river, which have been reduced by the construction of a cascade of hydropower dams in the upper river (Figure 5.25). The Tana Delta is a Ramsar-listed wetland that has high value for both biodiversity and tourism. However, the delta and upstream river are under increasing development pressure, including from an expansion of irrigated agriculture that poses conflicts with traditional land management and from the proposed 700 MW High Grand Falls dam, which would also divert water for municipal and agricultural use.

TANA RIVER BASIN

Location: Kenya

Basin type: current development, water scarce

Basin size: 95,000 km^2

Basin population: 6,500,000

Mean annual flow: 240 cms

Resources considered in case study: hydropower, fish harvest (floodplain and bay), floodplain grazing

Key result: Cascade reoperation options offer potential to improve generation by nearly 20 percent with modest gains in fish harvest and floodplain grazing, or to increase floodplain fish harvest and livestock grazing by 10-15 percent, with six percent increase in generation.

Upstream of the proposed High Grand Falls, the existing cascade consists of five hydropower dams, three with storage and two operated as run-of-river (ROR), with a combined installed capacity of 567 MW that provides around 40 percent of Kenya's electricity. The upper-most dam in the cascade (Masinga) stores the largest amount of water and regulates flows of the cascade below it. The three storage dams also support irrigation and water supply to local towns. The basin provides 95 percent of Nairobi's water supply through inter-basin transfers from two reservoirs (the Thika and Sasumua) on tributaries, which join upstream of the hydropower cascade.

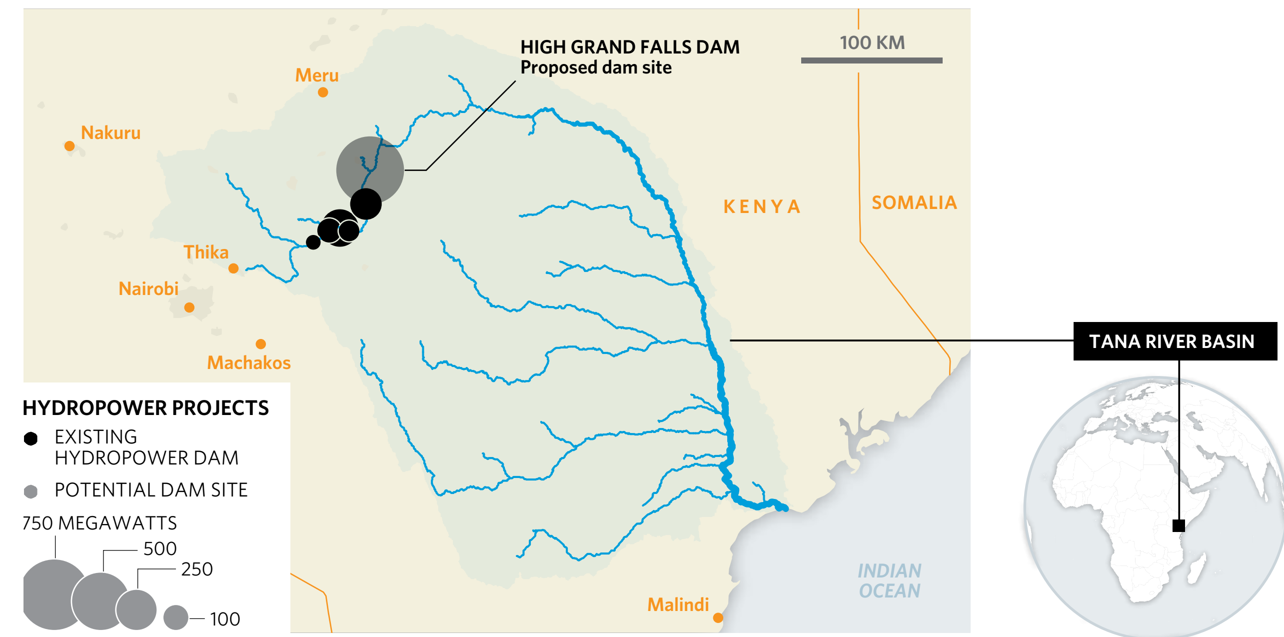
The operation of the hydropower cascade has many potential impacts on other sectors and services and this case study considers options for reoperating the cascade to produce different levels of benefits across some of those services.

136 Lead researchers: Anthony Hurford and Julien Harou (University of Manchester), supported by colleagues from the International Water Management Institute (IWMI), ODI, BC3 and ACCESS, under the IUCN-led WISE-UP to Climate Project. WISE-UP to Climate is funded by the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

137 The Nature Conservancy, "Nairobi Water Fund: Investing in Water".

FIGURE 5.25

The Tana River basin (Kenya).



Analysis

The existing hydropower cascade is reportedly operated to meet a contractual supply of electricity to Kenya Power of 172 GWh per month, which incentivizes the storing of water in the regulating reservoir once this target has been met to increase the probability of meeting the next month's target. Fines are imposed for failure to meet this contractual obligation, while only low rewards are provided for generating more electricity. Political pressure may result in the operator increasing generation, although this can reduce the probability of meeting obligations in subsequent months. The BaU for this case study assumes that the dams will be operated to meet this contractual obligation for hydropower generation as much as possible.

This case study assessed HbD options for reoperating the cascade as a system that also tries to improve downstream services. We compared the BaU case under the current contractual constraints to HbD options unconstrained by contract conditions and considered the potential for improvements in generation and other metrics (for more details on methods, see "tradeoff analysis" in Appendix E).

The following metrics were used to evaluate performance of the system under the BaU and HbD options and their different operating rules for the cascade:[138]

Mean annual generation: the total generation in GWh from all five hydropower dams in the cascade. This metric was maximized.

Floodplain fish catch: tons of fish caught on the floodplain and in oxbow lakes replenished by larger flood events. This metric was maximized.

Livestock grazing on the floodplain: millions of heads of livestock (cattle, goats, camels combined) which can graze on pastures sustained by flood waters and nutrients from sediment. This metric was maximized.

138 McCartney, in press

© NICK HALL (CHANIA FALLS, UPPER TANA WATERSHED, KENYA)

Trade-off analysis results

As long as the contractual obligation is in place, HbD options could only reduce the level of hydropower generation compared to the BaU option, as the BaU option represents the maximum possible generation with the contractual constraint. Removing the constraint of generating hydropower to meet the contractual monthly target provides a range of options for rebalancing the benefits from the system (Figure 5.26 and 5.27). Notably, options exist to increase hydropower generation, although with Options D, sacrifices to one or more other benefits are required. Although some options achieved increases in floodplain benefits at the cost of generation (e.g., options G), option E provides almost 20 percent increase in hydropower generation with small increases or no change in all the other metrics. Perhaps providing the best balance across metrics, option F provides 10-15 percent increases in floodplain benefits along with a 6 percent increase in generation, compared to the BaU.

These results illustrate the potential benefits from reoperating existing hydropower reservoirs as a system and seeking options that can provide a better balance of benefits. The current contractual arrangements for hydropower generation from the cascade appear to not have been designed to consider other basin benefits. A system-scale approach to reoperation of this cascade has the potential to maintain or increase generation while providing greater downstream benefits for ecosystems and people.

FIGURE 5.26

Tradeoff analysis for the Tana River comparing HbD options for reoperating the cascade, free from the contractual constraint (blue and gold dots) and the BaU (black dot). In a pareto-optimal sense, the HbD options dominate the BaU option. The gold dots indicate the HbD options displayed in Figure 5.27.

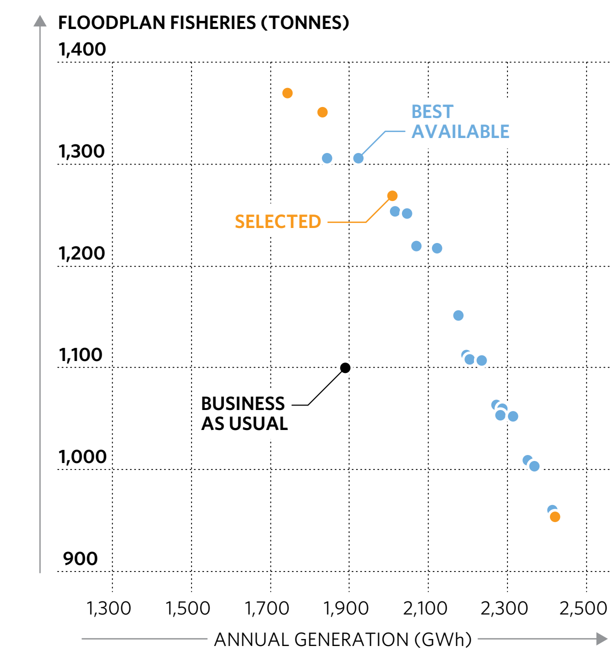
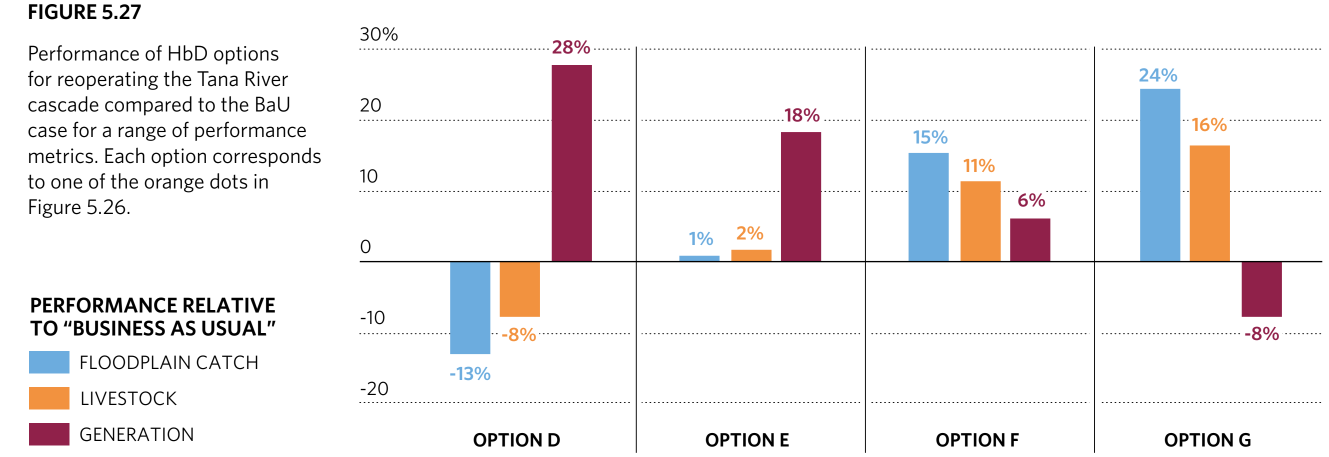
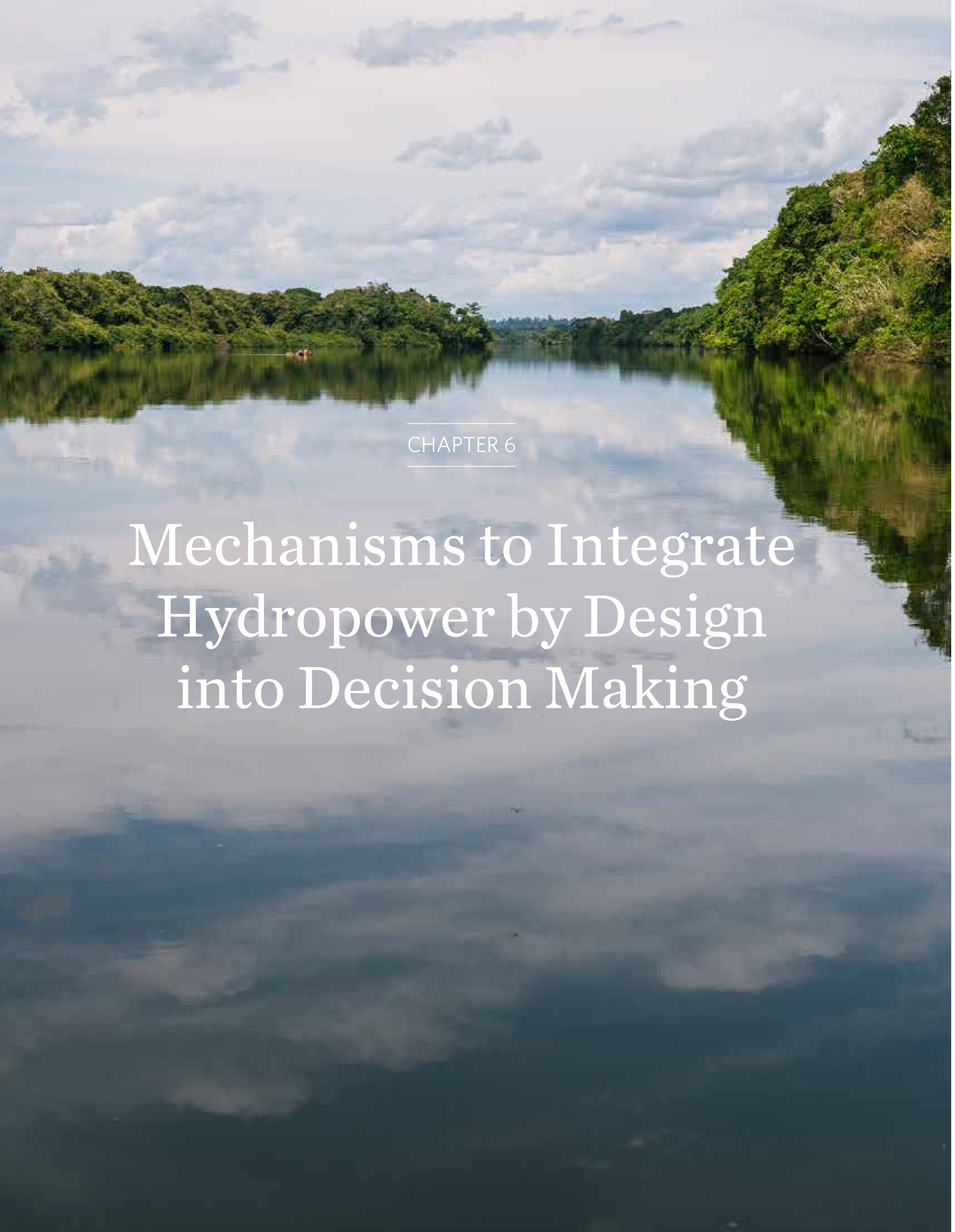


FIGURE 5.27

Performance of HbD options for reoperating the Tana River cascade compared to the BaU case for a range of performance metrics. Each option corresponds to one of the orange dots in Figure 5.26.





CHAPTER 6

Mechanisms to Integrate Hydropower by Design into Decision Making

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Hydropower by Design (HbD) draws on a range of existing best practices for guiding sustainable hydropower at scale, ranging from the project to the river basin, grid, country or region. In this chapter we explore how principles and components of HbD can be integrated into a range of existing mechanisms for planning and managing hydropower and rivers.

Recommendations for system-scale approaches to hydropower planning and management are not new, thus a major focus of this report is to articulate the economic and financial benefits of these approaches and demonstrate that they are feasible to implement.

We used a focused case study on Colombia's Magdalena River basin to demonstrate the sources of financial value created by HbD and explored how this financial value could be used to "pay for" more strategic and lower impact systems of hydropower development. Through a range of case studies, we illustrated how HbD can often deliver more-balanced outcomes from hydropower development and/or management, resulting in economic improvement for other values for similar levels of energy generation and/or investment. Through these examples, we believe that there is sufficient evidence for the financial and economic benefits of HbD that it warrants serious consideration and exploration by various institutions within the hydropower sector.

CHAPTER 6 KEY POINTS

- Hydropower by Design can produce real economic and financial value and the case studies illustrate several ways that integration of various models, sources of information and stakeholder perspectives can provide useful information to decision makers. In short, HbD can overcome some existing data and methodological constraints and is technically feasible to incorporate into planning and management processes.
- HbD can be integrated into a wide range of planning, regulatory, risk-screening and other management and decision-making processes, meaning that HbD doesn't necessarily require adoption of new policies.
- Various parts of the hydropower sector can adopt or support HbD:
  - o Governments can incorporate the principles of HbD into planning, environmental review, licensing and mitigation programs.
  - o Financial institutions and developers can incorporate the principles of HbD into risk-screening procedures, using the concepts to improve decisions on which projects to pursue and how to design and operate them.
  - o Early planning/project preparation facilities can provide both funding and technical capacity to integrate the concepts of HbD into government planning to identify a set of bankable projects that also contribute to broader strategic goals.

Catalyzing that uptake and exploration also requires demonstrating that implementation is feasible. The feasibility of implementation is a function of both technical practices and policy and regulatory conditions. The case studies give insights into technical feasibility as they demonstrate some modeling methods that can deliver usable results to practitioners and decision makers. For example, the tradeoff analyses can compare a huge range of investment options relatively quickly and identify those that have the potential for achieving outcomes that perform well across multiple objectives. This information can be fed into planning and decision-making processes and identify options that should receive greater scrutiny. Thus, this analytical approach can avoid the stereotypical concern that strategic planning requires years to deliver results. Similarly, the Magdalena case study showed that even a sophisticated integration of several models can deliver insights—about both system-level performance and project-level financial viability—relatively quickly and at reasonable costs.

Beyond the technical feasibility of analytical methods, for HbD to make a difference for sustainable development and conservation, it must be incorporated into the policies and practices of the key actors within the hydropower sector. Here we focus on opportunities for governments, hydropower companies and financial institutions.

Hydropower by Design can be viewed as a synthesis of a range of existing best practices across a number of dimensions, including planning, environmental and social review, licensing, mitigation, and project design and operation. Thus, there are elements of this framework that can be adopted by hydropower developers, financial institutions that fund hydropower and government agencies, including those that plan energy development, those that review and license infrastructure projects and those that manage environmental and social resources. Generally, the principles of HbD can be deployed through existing policies, regulations and other mechanisms. These include risk screening, corporate safeguards, environmental review processes—including Environmental and Social Impact Assessment, Strategic Environmental Assessment and Cumulative Impact Assessment—and policies for planning, licensing and mitigation. In other words, a specific entity, such as a government agency, does not necessarily have to adopt a new program called "Hydropower by Design," Rather, it can compare existing practices to the principles of HbD and strive to integrate those principles into existing mechanisms.

In this chapter, we first provide an overview of different roles governments, developers and financial institutions play in pursuing or supporting HbD and then review specific mechanisms for implementation.

Institutional roles with respect to Hydropower by Design

Governments will generally have the greatest ability to implement the concepts behind Hydropower by Design, particularly through their role in planning energy systems and licensing individual projects. The extent to which government planning determines site selection and design of projects varies considerably. In some countries, government agencies conduct energy and river basin planning and determine which sites will be built. In many countries, however, central governments conduct little planning and are generally reactive to plans proposed by developers.

If a government does not actively plan and select projects, other existing and commonly used policy or regulatory tools—such as energy auctions, Strategic Environmental Assessments, Environmental Impact Assessments and licensing—can be implemented or refined to move hydropower development away from a single-project focus and toward a system approach. For example, energy auctions to select the next generation of projects can be designed to promote investments in certain regions and technologies. The incentive to participate in auctions can be exclusive access to a site, payments for firm energy or capacity, a guaranteed feed-in tariff, or other advantages. Environmental assessments can include a robust review of siting and design alternatives. The licensing process can exert strong influence on which projects are built. It can also direct mitigation funding toward protection of areas identified as priorities during a HbD process. Licensing agencies can identify areas for which licenses will not be granted and, for those that are granted, determine their mitigation requirements, such as setting compensation ratios based on what is impacted. Colombia is integrating this approach into their licensing process for large infrastructure, including hydropower (see below and Appendix B).

Governments also have the ability to negotiate with other governments on issues that affect two or more countries, in cases of transboundary river basins and regional power grids. Ideally, neighboring countries could jointly plan the best possible hydropower systems and share the benefits. For example, if one country has a low-impact and low-cost site available for a large storage project, its neighbor could import power in times of drought. In reality, however, such arrangements have proven difficult, with many governments unwilling to share responsibilities and sovereign decision-making powers. Formal regional arrangements and international conventions can be helpful to reassure governments that costs and benefits will be shared equitably.

Some *developers* with a dominant market position and, in particular, public utilities with regional or national monopolies, are in a strong position to adopt HbD principles. While other developers may not have the ability to plan or manage at the scale of a system, they can follow policies or practices that support the principles of HbD, such as by adopting corporate sustainability standards or by using risk-screening tools such as the Hydropower Sustainability Assessment Protocol to guide which projects they choose to pursue. Further, companies that recognize the value of reducing risk for hydropower development could signal their support for Hydropower by Design to governments and funders and contribute to its adoption.

Diverse *financial institutions* fund hydropower projects, including private commercial banks, state-owned development banks, multilateral institutions, such as the African Development Bank, and bond markets. Financial institutions can integrate the principles of Hydropower by Design into their environmental and social policies to determine which projects they will fund and/or to attach conditions to their financing, such as mitigation requirements. Although multilateral financial institutions have comprehensive environmental and social safeguards, they are generally applied at the project scale. A recent review of hydropower standards by the International Institute for Environment and Development[139] concluded that "few standards or safeguards" address system planning or options assessments that can "screen out" bad projects. Even when focused at the project scale, however, safeguards can be implemented in a way that supports the principles of HbD. For example, if applied early enough, project-level safeguards can help avoid building projects in projects that have particularly high costs in terms of system-level environmental or social resources. Further, application of safeguards at the project scale can trigger mitigation funding that contribute to supporting broader conservation goals, for example through the protection of an "offset" river.

Multilateral financial institutions can also promote mechanisms such as Strategic Environmental Assessments and early planning facilities. They can provide funding and technical assistance to governments to support system-scale planning, resulting in a pipeline of projects that are consistent with a system plan.

The IIED review reported that approximately 85 percent of hydropower projects globally are not covered by any set of international safeguards and suggested that hydropower-related risk screening tools can be particularly useful for projects developed in the absence of safeguards. In the absence of rigorous safeguards or regulatory structures, risk-screening tools can provide important information to help investors and developers integrate the concepts of HbD into their decisions about which projects to pursue. IIED suggested that the Hydropower Sustainability Assessment Protocol ('the Protocol') is currently the most effective evaluation tool to measure project sustainability (see below). The Protocol can also serve as hydropower-specific complement to general safeguards. The World Bank is promoting the use of the Protocol as a risk screening tool that can be applied in advance of applying its own safeguards.[140]

139 Skinner, et al., 2014.
140 Liden, et al., 2014.

Implementation Mechanisms for Hydropower by Design

National planning

A number of countries already have a national planning process for the expansion of their power generation systems. However, as implemented in the Latin American region (and see Box 6.1 on Brazil),[141] most of these have not effectively accounted for environmental, social and water resource management issues. Most are indicative and not binding. However, even indicative plans can be useful to provide some idea of future demand and supply, to prepare energy auctions and to plan for other parts of the system, such as the transmission network. While in their current form these types of plans do not contribute much to resolving conflicts over hydropower, they could be modified to be more comprehensive and include many of the principles of Hydropower by Design (see Appendix A).

Two Nordic countries with the highest generation of hydropower per capita in the world are perhaps the best examples for master planning to achieve balanced outcomes with hydropower. Both have made country-wide efforts to identify all potential remaining sites, as well as sites that will not be developed (i.e., rivers that will be protected). Although conflicts over hydropower development have not disappeared, the methods and choices are transparent and have been legitimized by parliamentary approval.

Norway's government developed a Master Plan in the 1980's to provide a national assessment of river resources and to rank future hydropower projects. In addition to energy generation, the Master Plan assessed resources such as fish and wildlife, recreation, cultural/historical sites and other water sectors such as water supply and flood management. Currently, 389 rivers or parts of rivers are protected, illustrating how formal protection of river systems can be an important part of, or complement to, national energy or hydropower planning (Box 6.2).[142]

Following Norway's example, Iceland started a master-planning process in 1999 that is now in its third phase and covers all energy projects in the country (hydropower, geothermal and wind power). In 2011, after the controversial 690 MW Kárahnjúkar project had been built, a regular four-year planning cycle was established by law. An independent Steering Committee is appointed every four years to evaluate projects suggested by the National Energy Agency and the power companies.[143]

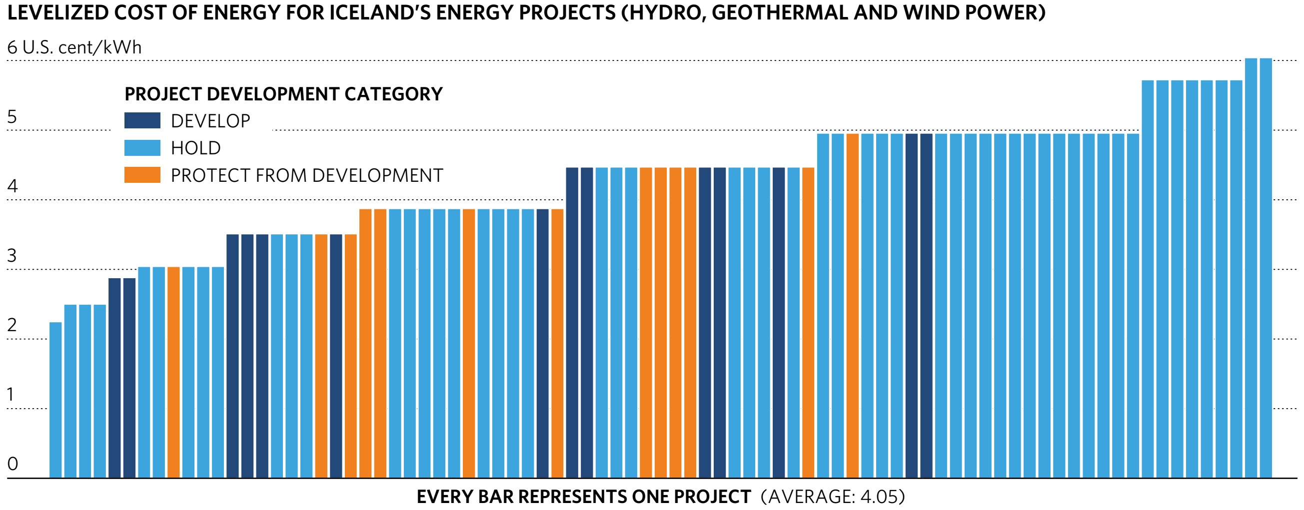
Figure 6.1 shows the conclusions of the second master-plan phase. The 79 available project sites are ranked by levelized cost of energy (LCOE) and placed into categories for development status (dark blue: develop; light blue: hold for future evaluation; orange: protect from development). The general tendency of the master-planning committee has been to favor geothermal and wind projects over hydropower, even if they are slightly more expensive and will increase the average cost of power in Iceland. How much more power capacity will be developed in Iceland depends on the appetite for attracting even more power-intensive industries, such as aluminum smelters and data centers, and whether a submarine cable will be laid to Europe to benefit from much higher power prices there.

The success of institutionalized national planning depends not only on its technical quality. As the example of Brazil shows (Box 6.1), planning is a complex endeavor and designing a satisfactory planning system is difficult.

141 Hartmann, et al., 2013.
142 Moir, et al., 2016.
143 Askja Energy, 2016.

FIGURE 6.1

Results of Iceland's second master plan for expansion of electricity capacity. The 79 available project sites (wind, hydropower and geothermal) are ranked by levelized cost of energy (LCOE) and placed into categories for development status (dark blue: develop; light blue: hold; orange: protect from development).



BOX 6.1
Brazil and national hydropower planning

Brazil has often been viewed as an example for a country with a sophisticated planning system and the technical capacity to deliver well-conceived hydropower projects. The core principles of the process generated a lot of interest in other countries: the government selected projects that are supposed to be in the best public interest by systematically planning, basin by basin, identifying projects and auctioning off these projects to developers. The process was intended to ensure low power prices and to recover planning costs from developers. However, over time, this process has faced increasing problems:

- The environmental licensing is not integrated into planning, leading to uncertainty. Planners use different criteria and come to different judgements about project impacts than the environmental agency and the courts. In some cases, most recently at the 8 GW São Luiz do Tapajós project, licenses have been denied after decades of expensive preparation. A World Bank study estimated that the costs of environmental licensing were, on average, 15.2-20.1 percent of project costs. However, only 12.0-12.5 percent are "useful costs," defined as investments in social and environmental improvements. The rest is due to regulatory uncertainty and to the opportunity cost of delays, leading to higher-cost projects being built first.
- Despite the planning emphasis on system reliability, especially during droughts, no storage projects have been built in recent years. Brazil is increasingly relying on run-of-river projects in the Amazon. Some of those projects are very large—for instance Jirau, Santo Antonio and Belo Monte, with a total capacity of 18 GW—but have very little active storage.
- The planning and decision-making process is centralized, not transparent and technocratic. Stakeholders—in the case of the Amazon, often indigenous communities—are not involved and are not convinced that their interests are being taken into account. Their resistance has contributed to significant delays and cost increases at the 11.3 GW Belo Monte project, for example.
- Water governance responsibilities are divided between multiple agencies and levels of government, leaving room for improvement in the allocation of water between hydropower and other water-using sectors.[144]

These problems, combined with corruption and political interference, have led to a loss of public confidence in the planning system. Belo Monte, in particular, has polarized the debate, with many questioning its economic justification. As the Economist has stated:

> "Such disagreements are best settled by estimating costs accurately. Brazil's institutions are ill-suited to this. Planning and environmental laws are Byzantine: getting licenses and fighting legal challenges routinely adds years to schedules and billions to budgets. The result is more like an obstacle course than a cost-benefit analysis. The environment ministry and regulators play almost no part in deciding which projects go ahead: their main role is harm reduction after the energy ministry has decided what to do. Both have seen bosses resign rather than sign up to infrastructure projects in the Amazon. These failures mean that the most important question—whether Belo Monte is really cheaper than the alternatives—has never been satisfactorily answered."[145]

144 OECD, 2015.
145 The Economist, 2013.

BOX 6.2
Formal protection of rivers: an example from Norway[146]

Norway relies almost entirely on hydropower for its electricity and most of its large rivers are currently regulated. By the 1970s, approximately half of Norway's estimated hydropower potential had been developed and new hydropower projects began to confront opposition from indigenous groups, environmental organizations and other proponents of non-power values from rivers. As energy demand continued to increase, the government of Norway decided that a project-by-project approach to hydropower development was not capable of producing outcomes that balanced the multiple values of the country's rivers.[147] In response, Norway implemented a set of planning processes, policies and regulations that now govern how hydropower is developed and managed, including formal protection of rivers.

Through multiple legislative actions in the 1970s and 1980s, Norway created a national Protection Plan for Watercourses which, by 1986, had designated nearly 200 rivers or stretches of river for protection, including removal from eligibility for future hydropower licenses. In the 1980s, the government developed a Master Plan for Water Resources to provide a national assessment of river resources and to rank future hydropower projects with the goal of meeting an energy target with the lowest impacts on other resources, including the environment. By ranking projects across a range of economic, social and environmental criteria, the Master Plan established a category for projects that should not be developed due to their impacts. In part based on the Master Plan's ranking and categorization scheme, the Protection Plan for Watercourses has now grown to include 389 rivers or parts of rivers representing approximately 40 percent of Norway's river basin area which supports approximately 25 percent of Norway's hydropower potential.[148]

In 2003, the Norwegian Parliament also established a system of "national salmon rivers," a designation which prioritizes management and restoration of Atlantic salmon stocks and precludes activities that would harm wild salmon. A total of 52 rivers have received this designation, representing approximately three-fourths of Norway's production of wild Atlantic salmon.

Because of Norway's dependence on hydropower, it has developed a very high proportion of its rivers. However, Norway has also formally protected more rivers than any other country and its Master Plan directs large hydropower development toward low-conflict rivers and away from high-conflict rivers. As a result, Norway continues to depend on hydropower while protecting a significant share of its rivers and reducing conflict. This illustrates that formal river protection can be an important part of comprehensive energy planning, which can increase certainty for energy planners, developers, investors and those stakeholders focused on other values of rivers.

146 Adapted from a case study written by J. Opperman and others within Moir, et al., 2016.
147 Huse, 1987.
148 Stensby and Pedersen, 2007; Freiberg, et al., 2010.

Risk screening

As evidence of hydropower impacts and conflicts has grown over time, government regulators, financiers, industry groups and civil society organizations have developed regulations, guidelines and assessment tools to reduce risks and improve the quality of projects. Governments always have a role in screening hydropower projects, whether for licenses, concessions, permits, power purchase agreements or public funding.

Banks have also issued specific guidelines for risk screening.[149] Since hydropower projects are capital-intensive, access to loans from commercial and development banks is a major consideration and banks can exercise influence over project choice and design. Banks protect themselves from material and reputational risks, ensuring that projects they fund are in line with their sustainability policies, through lending guidelines or safeguards. These are usually generic across sectors, though in some cases banks have issued specific guidelines, such as the World Bank on dam safety and HSBC on freshwater infrastructure lending. Sustainability commitments by banks either reference their own standards or other international guidance. The Equator Principles require compliance with the Performance Standards of the International Finance Corporation (IFC) and have been adopted by close to 80 banks, covering over 70 percent of international project finance debt in emerging markets.[150] Bond markets are also taking steps to reduce impacts. The Climate Bonds Initiative is in the process of designing criteria for hydropower bonds. Access to these sources of capital can be a strong incentive to select low-impact projects for development.

The Hydropower Sustainability Assessment Protocol (the 'Protocol') was developed by a multi-stakeholder forum.[151] Because it does not define what constitutes an acceptable level of sustainability, the Protocol is not a standard, but rather an assessment tool used to measure and guide performance in the hydropower sector. It can be applied to assess projects that are in different stages of development—preparation, implementation or operation—and, for each stage, scores relative performance across 20 or more sustainability topics ranging from economic and financial to environmental and social factors. Importantly, it also contains a section for evaluating a potential project at the early planning stage, considering such factors as the demonstrated need for the project and the assessment of alternative options.

The screening tools described above are largely oriented towards individual projects. The best they can do is to test whether this individual project has been compared against alternative options and has emerged from a planning process. There has been an attempt, however, to develop one of them into a basin-level screening tool. The Rapid Basin-wide Hydropower Sustainability Assessment Tool (RSAT) was developed in 2010 by the Asian Development Bank, the Mekong River Commission and the World Wide Fund for Nature (WWF). The objective of the RSAT is to "assess hydropower sustainability within an IWRM based framework."[152] It is composed of 10 topics and 27 sub-topics. Similar to the Protocol, the RSAT is a tool for measuring sustainability, although the RSAT places greater emphasis on river-basin planning and can be used to evaluate a system of hydropower projects. While developed for the Mekong basin, it can be used in or adapted for use in other regions.

Risk-screening tools can also serve as standards for certifying a level of performance needed to achieve a certain status, such as eligibility for a subsidy or access to advantageous financing or specific market. For example, the European Trading System for carbon credits determined that a hydropower project could only be eligible to participate in that market if it was "compliant" with the seven strategic priorities of the World Commission on Dams (even though the WCD was not established as an actionable mechanism for assessing a project). Recently, there has been some discussion of how the Protocol could be used to help determine eligibility for certain sources of climate financing. Renewable Portfolio Standards and the The Low Impact Hydropower Institute (LIHI), a non-governmental organization that certifies "environmentally preferable" hydropower in the United States, provide an example of linking project performance to advantageous markets (Box 6.3).

149 Georgoulias, 2017.
150 Equator Principles III, 2013.
151 IHA, 2010.
152 United States Agency for International Development, et al., 2010.

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BOX 6.3
"Environmentally preferable" hydropower and preferential markets

Many states within the US have established Renewable Portfolio Standards (RPS) which require a certain proportion of electricity within the state be generated from renewable sources. For example, California has a RPS mandating that 50 percent of generation come from renewable sources by 2030. Generation sources that qualify as renewable under the RPS can often receive a price premium on the electricity they sell. In the states where hydropower qualifies for the RPS, it is frequently limited to "small hydropower" (e.g., those projects with less than 30 MW). Conservation organizations have generally resisted including hydropower within RPS, or expanding beyond small projects, due to concerns about both environmental impacts and that counting hydropower—often a source with a sizable proportion of a state's generation already—would reduce the incentive for new wind and solar. However, some conservation organizations have supported the inclusion within RPS of hydropower demonstrate a commitment to environmental safeguards through certification by the Low Impact Hydropower Institute (LIHI). Currently, four states allow LIHI-certified projects to qualify for their RPS.[153] For example, in Massachusetts, LIHI-certified projects are receiving an additional 26 $US/MWh above standard prices. More than 130 projects have been certified by LIHI around the US.[154]

'Early Planning' Project Preparation Facilities

The consulting firm McKinsey estimated that global infrastructure investments are only meeting about half of a US$6 trillion annual demand, with more than half of this gap concentrated in power sector projects.[155] Others have calculated lower requirements, but agree that there are large gaps. Large infrastructure projects typically have important public-good characteristics, require large-scale capital mobilization and are subject to political and regulatory uncertainties. These conditions are particularly true for hydropower given the sector's multiple-use capabilities, the variety of ancillary energy services offered and the many stakeholders that can be affected.

Development banks have historically played a strong role in financing large-scale infrastructure projects. However, the ongoing privatization of the power generation sector has led to a marked decline in the governmental planning and coordination capacities needed to shepherd projects, creating challenges for licensing and securing power purchase agreements. Moreover, an ever-expanding array of requirements of the banks have raised the bar for project preparation. Most recently, climate-change mitigation and adaptation requirements were added.

A lack of certainty regarding future power demand and supply, combined with uncertain return profiles and long payback periods, means it is hard for hydropower developers to justify investing capital in the required levels of project preparation. Absent such investment, development banks have an insufficient "pipeline" of future projects for them to offer loans. As described by the World Bank's Bertrand Badré in October 2015: "There are simply not enough viable projects out there."[156] Meanwhile, projects funded by other sources often have not conducted the level of project preparation required to achieve high levels of sustainability.

These issues are further compounded within the hydropower sector as the highly site-specific nature of these projects—for example, from a geotechnical, hydrological and regulatory context—significantly raise preparation time and costs. While most energy projects require 1 to 5 percent of total project cost be spent upfront on non-capitalizable planning costs, this figure routinely rises to an average of 8 percent for hydropower projects.[157]

153 Stori, 2013.
154 LIHI, 2017.
155 Bielenberg, et al., 2016.
156 Authers, 2015.
157 IFC, 2015.

It is against this backdrop, that development banks have been creating specialized project preparation facilities (PPFs) designed to help projects achieve the necessary benchmarks and documentation to make them bankable. These facilities can fund feasibility and environmental studies, legal analyses and transaction structuring to make projects attractive to investors. They also can provide a framework to help governments meet strategic priorities for infrastructure and develop a realistic pipeline of projects to meet those targets.

These PPFs are typically targeted towards "midstream" activities—projects that are already part of the government's existing infrastructure buildout plan or engineering surveys of potential sites. However, as discussed throughout this report, many of the most important factors that affect environmental and social impacts and sustainability can only be appropriately addressed at an even earlier stage, as project options and sites are first identified. Such "upstream" analysis is the essential opportunity for Hydropower by Design. Box 6.4 describes how PPFs can be augmented to also fund "upstream," early planning activities.

For hydropower, an early planning project preparation facility could support "upstream" planning that first identifies an inventory of potential project sites, consistent with both investment risk/return criteria and criteria focused on social and environmental sustainability. These sites would then be prepared with traditional midstream approaches to make them bankable and available to developers (see Box 6.4). Such a facility would motivate participation from a diversity of constituencies: governments, by helping meet renewable energy commitments and other strategic targets; developers, by providing a risk-reduced pipeline of projects; development banks, by creating a loan pipeline for the same risk-reduced pipeline; and social and environmental civil society organizations, by establishing a development framework in which their perspectives could be incorporated during influential early stages of planning.

Mitigation Policies

Environmental mitigation is generally implemented at the level of individual projects and conservationists have often criticized that mitigation policies lead to actions with limited or piecemeal benefits. However, even when triggered by individual projects, mitigation can be targeted toward achieving system-scale objectives that address cumulative impacts and realize meaningful conservation benefits. Thus, mitigation policies and programs implemented at the project-level can advance many of the system-scale principles of HbD.

Mitigation that effectively addresses system-scale objectives can be guided by application of the mitigation hierarchy—avoid, minimize, restore, offset—informed by conservation planning.[158] Conservation plans indicate the priorities for protection or restoration that inform decisions about where project impacts should be avoided and where offset investments should be sited to deliver the most benefit.

From a hydropower perspective, this combination of conservation planning and the mitigation hierarchy can be used within project licensing and mitigation to guide decisions and direct resources to:

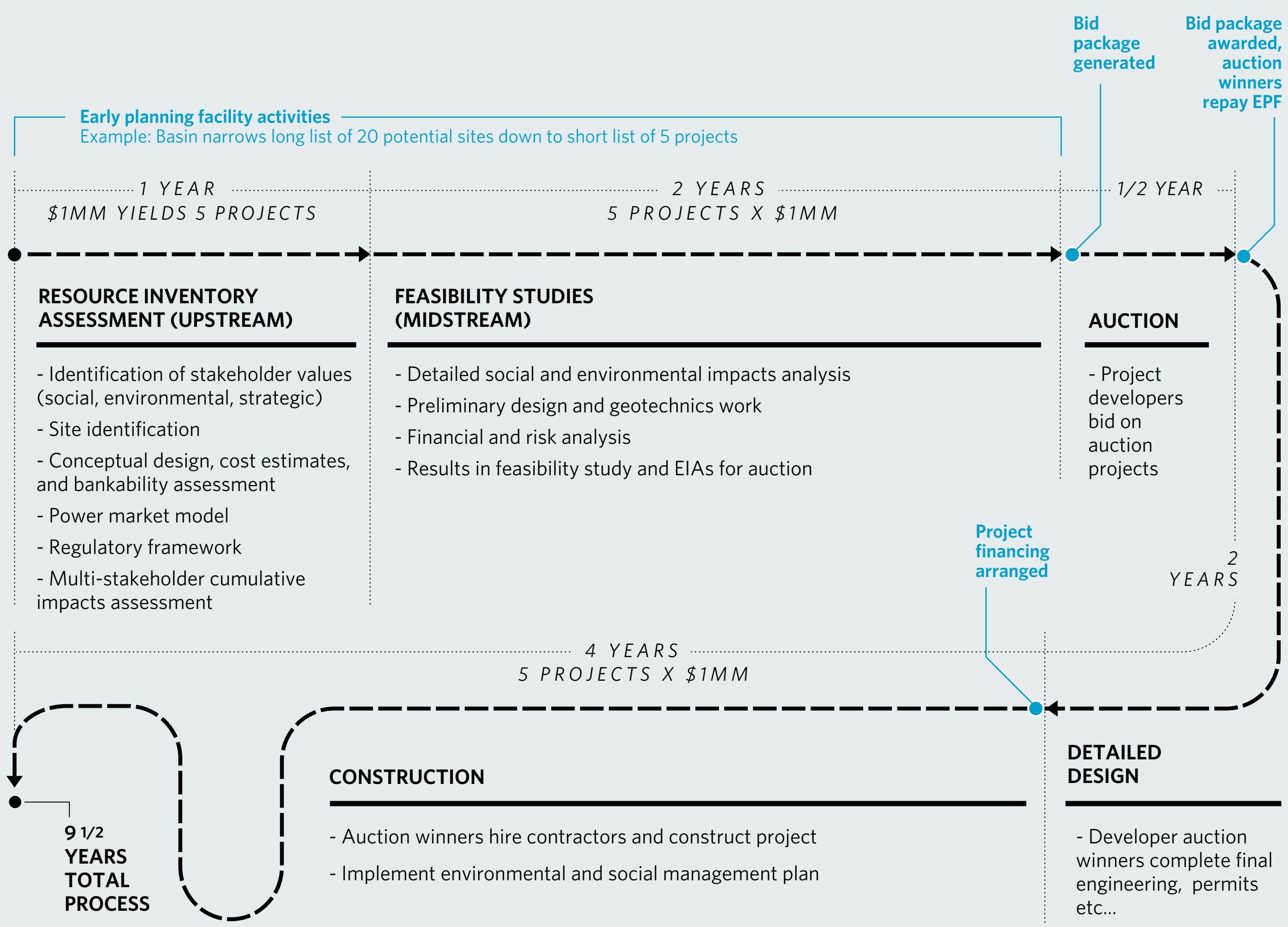
1. **Avoid:** Licensing processes can be used to ensure that new projects avoid the most damaging sites and to direct development toward sites that result in less impact
2. **Minimize impacts:** Licensing can place mitigation conditions on project design and operation, such as fish passage structures and/or the release of environmental flows to minimize impacts from hydropower projects.
3. **Offset:** Some projects will have a set of impacts that cannot be avoided or minimized (i.e., "residual impacts"). Residual impacts can be addressed through offsets or compensation—actions intended to produce environmental gain by restoring or conserving similar resources as were negatively impacted by the project, with the aspiration of contributing to "no net loss" or even a net gain for that type of resource.

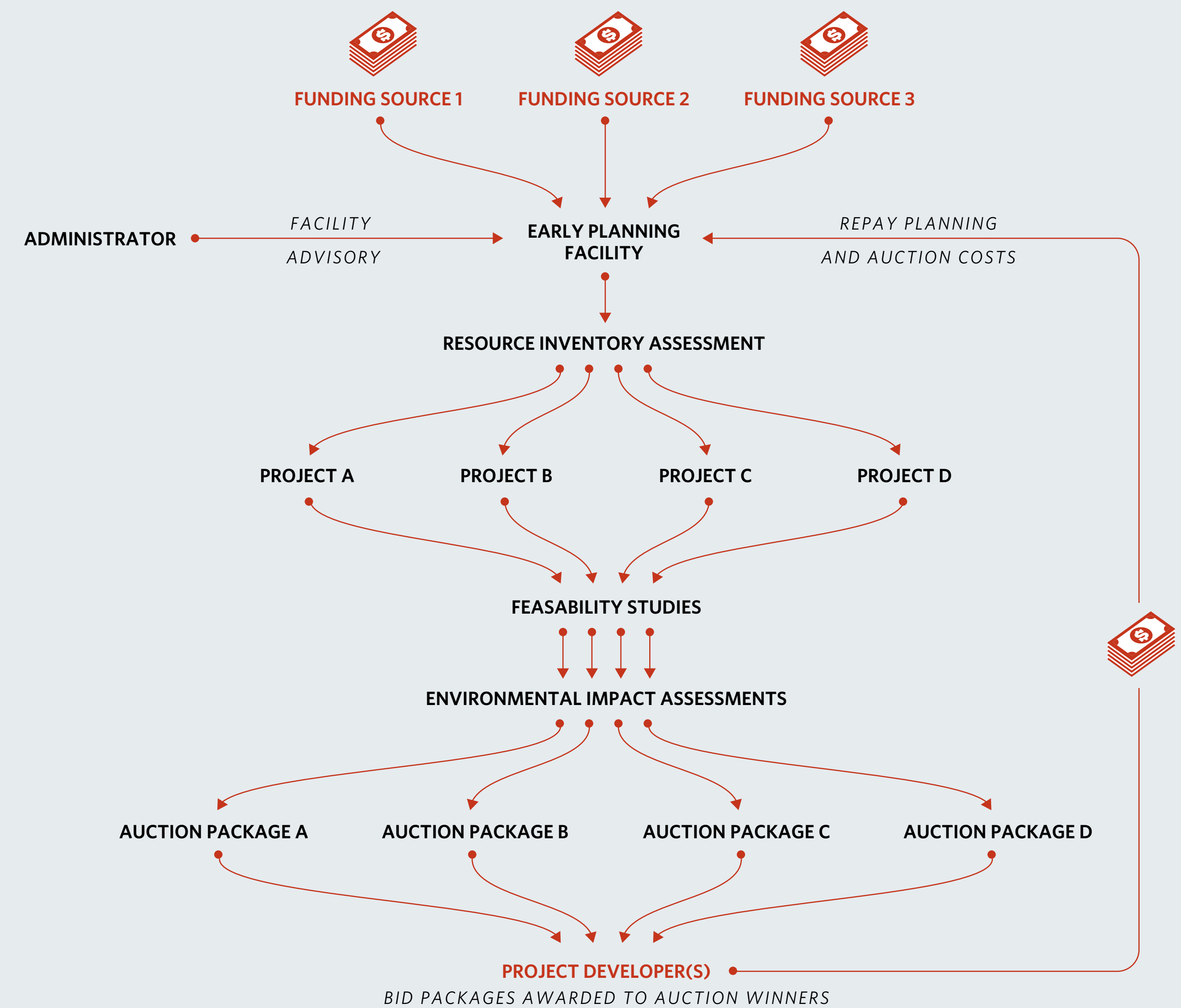
158 Kiesecker, et al., 2009.

BOX 6.4
Diagrammatic Example of Early Planning Project Preparation Facility

The figures in this box provide an illustration of how a project preparation facility could generate a series of bankable and sustainable hydropower projects by supporting a range of "upstream" (early planning) and "midstream" activities. This conceptual design is loosely modeled after the preparation procedure used by Brazil's energy planning agency (Empresa de Pesquisa Energética (EPE)) in selecting hydropower sites.

The figure on the left depicts the operating activities that an early planning facility would support, while the figure on the right describes the flow of funds to support the operating activities. Note that it is possible for well-managed project preparation facilities to remain "evergreen" by having the preparation costs paid for by project developers, for example as part of the auctioning of the selected sites. This mechanism would provide a way for the project developer community to contribute toward planning consistent with HbD.





While minimization measures may be most relevant for project-level best practices, avoidance and offset measures can be directly aligned with the system-scale principles within HbD. Rigorous application of these steps could replicate some of the outcomes that could emerge through a comprehensive plan, as both could protect the most important rivers, direct development to lower-impact areas and target offset investments toward places that will most effectively achieve conservation objectives. However, on its own, mitigation does not capture some key components of HbD, such as the assessment of multiple options to quantify tradeoffs and identify those options that work well across multiple dimensions. But mitigation policies are common across the world and thus represent a potential entry point for the integration of the principles of HbD into existing policy and regulatory structures.

Mitigation offsets can be applied as a condition of project approval or funding. For example, in Costa Rica, the national power company (the Instituto Costarricense de Electricidad, ICE) sought to build a new hydropower project on the Reventazón River. The new project would be the most-downstream dam on a cascade of four hydropower dams. ICE agreed two forms of conservation offset with the project's funder, Inter-American Development Bank (IDB). First, the dam's reservoir was within a migratory corridor for jaguars and so ICE restored forest cover to improve other portions of that corridor to maintain the ability of the big cats to move through that area. Second, the new dam would negatively impact migratory fish species, and so Costa Rica's government designated the neighboring Parismina as a free-flowing river in perpetuity. The Parismina joins the Reventazón near its mouth and so can provide habitat for the same migratory fish species.[159]

Poor water quality in the Parismina is one of the primary threats to the ability of migratory fish to use the habitat and thus the offset will also fund restoration and land-management practices to improve water quality. The Parismina is a considerably smaller river than the Reventazón, illustrating that a general challenge with offsets for rivers is finding a river or rivers to protect or restore that are sufficiently similar to the river that is being impacted. However, in this case, the river being impacted (the Reventazón) was already affected by three existing dams and the offset protecting the Parismina is notable for being one of the first river offset applied to a hydropower project.[160]

The process and outcomes that occurred on the Reventazón can be formalized within a country's mitigation policy. An effective policy can increase certainty for projects, reducing regulatory risks, ensure that mitigation investments are cost effective and contribute to meaningful conservation at large scales.

In Colombia, a series of laws and decrees have incorporated the mitigation hierarchy into the licensing process for infrastructure projects. Colombian law does recognize "avoid" as the first step in applying the mitigation hierarchy, with a designation of types of areas that are "no go" zones for development (e.g., national parks and other protected areas). Projects subject to an Environmental Impact Assessment (EIA) must offset their impacts on terrestrial ecosystems (as regulated by Resolution 1517 of 2012) and freshwater resources (Law 99 of 1993, Decree 1900 of 2006 and Decree 1933 of 1994). These policies were developed from a landscape conservation perspective and thus they establish clear links between offsets and broader conservation plans.

159 IDB, "Project snapshot: hydroelectric project takes unprecedented measures to protect habitat".
160 Moir, et al., 2016.

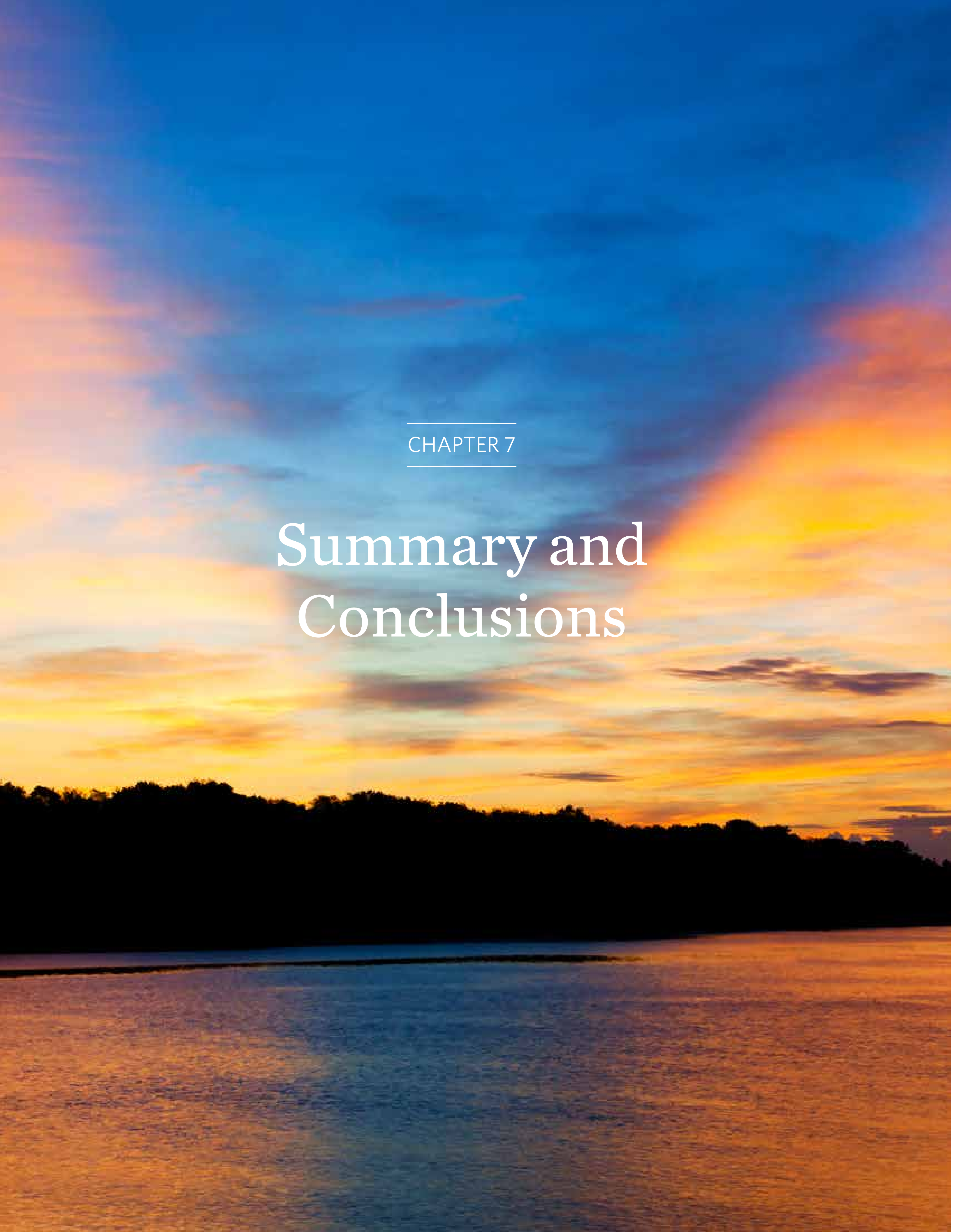
The policies require planned projects from sectors including mining and energy infrastructure to offset residual biodiversity impacts by restoring or protecting equivalent habitat. This principle of equivalence requires that both the amount and location of compensation be based on a series of measurable landscape features. The location of the offset is decided by the project developer and approved by the National Environmental Licensing Authority (ANLA). The developer is responsible for implementing the offset. The primary guidance for implementing offsets is the Manual for Allocating Offsets for the Loss of Biodiversity. The manual provides guidance on what requires an offset and then how much offset is required, where it should occur and how it should be implemented. The Nature Conservancy has helped the Ministry of the Environment develop, test and refine the manual. This policy is still in its early phases of implementation and there have been some challenges in its application. Offsets have been implemented for terrestrial impacts but not yet for impacts to rivers and other freshwater ecosystems or for coastal or marine ecosystems. See Appendix B for more discussion of this policy in Colombia and how it aligns with HbD.

Mitigation can also be applied to existing projects that have requirements for periodic re-licensing. Globally, only a few jurisdictions have time-bound licenses, which require licenses to be periodically renewed, and projects are subjected to a review of their performance. The societal benefit of a re-licensing scheme, such as under the United States Federal Energy Regulatory Commission (FERC), is that changes in expectations, new legal requirements and increases in environmental and social knowledge can be incorporated into updated license conditions.[161] Through the FERC relicensing process, projects can be required to invest in mitigation actions. While these actions have generally been limited to the project itself or its adjacent environment (e.g., fish passage or environmental flows), project-level mitigation can be directed toward meeting broader conservation objectives.[162] The Penobscot River (see case study in Chapter 5) illustrates this potential, as several hydropower projects received renewed licenses within a process that featured the removal of other dams and the restoration of hundreds of kilometers of habitat for migratory fish.[163]

The compensatory mitigation requirements could potentially be harnessed to direct conservation dollars toward meeting broader river restoration objectives. For example, in the United States, laws such as the Clean Water Act and FERC relicensing, discussed above, trigger mitigation requirements. A system of "compensatory mitigation funding" has arisen to address certain types of impacts, such as the filling of wetlands or the conversion of endangered species habitat. Compensatory mitigation funding now represents a US$3 billion marketplace, making it functionally one of the largest sources of conservation funding in the United States.[164] These dollars can be better optimized to support river restoration priorities.

These concepts could be applied toward achieving the sort of system-scale conservation gains illustrated by the Penobscot. "Current development" river basins often contain a high density of old dams that have long outlived their purpose and may even have become a dangerous liability. Although removing these dams would restore river connectivity, there is often limited funding to do so and while compensatory mitigation could direct considerable funds toward achieving these objectives, to date there have been limited examples of the practice. One example occurred in North Carolina, where mitigation funding triggered by requirements of the Clean Water Act was used to remove two dams.[165] Expanding to broader uptake will require developing specific crediting methodologies that quantify impacts and benefits to rivers to calibrate the "credits" and "debits." The Nature Conservancy is currently working with partners to develop these methodologies. There is also great potential to direct some portion of the millions of mitigation dollars generated through FERC relicensing toward removing outdated dams and achieving large-scale reconnections of rivers.

161 Pittock and Hartmann, 2011.
162 Owen and Apse, 2015; Opperman, et al., 2011b
163 Opperman, et al., 2011a.
164 Environmental Law Institute, 2007.
165 U.S. Army Corps of Engineers, 2008.



The world confronts a series of intertwined global challenges: maintaining a stable climate, delivering energy to support prosperous societies and protecting healthy ecosystems.

The solutions to those challenges read like a set of conundrums:

- A continued rise in emissions of greenhouse gases (GHG) threatens to push the planet's climate beyond safe and stable boundaries and thus strategies to reduce emissions are needed urgently.
- The generation of electricity represents one of the largest contributors to global GHG emissions, yet electricity is also a fundamental driver of prosperous and healthy societies—and more than a billion people (17 percent of global population) still have no access to electricity.[166]
- A dramatic increase in electricity generation from sources with low GHG emissions is therefore the critical path toward achieving the goals of a stable climate while maintaining prosperous societies and increasing access to electricity to those who don't have it.
- Hydropower is currently the world's leading source of electricity with low GHG emissions, with large remaining technical potential. Further, hydropower is the leading mechanism for storing energy and stabilizing grids—a service that will be particularly important as variable renewable sources, such as wind and solar, become a larger part of the energy mix.
- Yet hydropower causes significant negative impacts on resources that have great value and these impacts—on sources of food or livelihood—tend fall disproportionately on low-income rural communities and indigenous communities that often have few other options. A dramatic expansion of hydropower risks solving the climate crisis at the sacrifice of much of the world's rivers and what makes them unique and economically valuable to, and loved by, people.

This report explores solutions to these conundrums and reveals that there are pathways that can navigate through them. Energy development and generation will always have negative impacts. Tradeoffs are unavoidable. The cases in this report show, however, that many impacts can be avoided or reduced and that tradeoffs can be eased.

This reduction of impacts and easing of tradeoffs emerges by shifting the scale of the solution: decisions about how and where to build, or how to operate, can be moved away from the scale of individual projects and toward the scale of systems. In this report we explore the potential for this system-scale approach—what we call Hydropower by Design (HbD)—to achieve improved outcomes for people and nature during hydropower development and management.

Recommendations for system-scale approaches are not new and have often been equated with lengthy, difficult processes that slow investment and/or produce unrealistic recommendations. We recognize that to make a difference, HbD must be seen as: one, providing economic benefits to countries; two, financially viable; and, three, feasible to implement. This report is, therefore, organized as a business case to demonstrate to governments, developers and funders that HbD can meet those expectations.

166 IEA, "Energy Poverty."

Economic benefits to countries

In river basins across the world, hydropower development and management will interact with water management services—including water supply, flood-risk management and irrigation storage—that have an aggregate estimated value of US$285 and US$770 billion per year. Hydropower that is planned and operated as part of a larger system has the potential to increase the benefits from these services. However, hydropower that is not considered part of a system will tend to miss out on opportunities to benefit these services and can, at times, even conflict with them. Further, hydropower development will be concentrated within those river basins that support the highest levels of riverine fish harvest, the greatest extent of flood-recession agriculture and the highest diversity of freshwater fish species. The extent of environmental and social resources at risk to hydropower underscores the need for solutions that reduce impacts and deliver broader benefits.

Through a series of case studies, this report shows that implementation of HbD within river basins could result in improved performance in other important economic values in river basins, including irrigation, water supply and flood-risk management. These gains could often be achieved alongside large improvements in environmental performance, such as dramatic increases in the length of rivers accessible to migratory fish—ranging from hundreds to tens of thousands of kilometers within river basins.

The potential global economic benefits of widespread adoption of Hydropower by Design are large: even a 5 percent improvement in other water-management resources in river basins where hydropower plays, or will play, a major role would produce US$14 to US$38 billion per year in additional benefits, a sum comparable to average annual investment in hydropower.

Financial viability

A case study focused on the Magdalena River basin in Colombia examined the potential financial benefits of implementing HbD during planning and project selection. This required the integration of a set of models—encompassing water management, energy planning and financial assessment—that often are deployed in isolation. This analysis showed that HbD could identify hydropower development plans that could achieve a system that meets energy targets with lower environmental and social impacts and thus would be more economically strategic for Colombia. Importantly, we also showed that this system could be composed of individual projects that were financially competitive with a distribution of Net Present Value (NPV) that was higher than projects selected through a Business as Usual approach.

HbD offers two primary forms of financial benefit:

System design optimization: Hydropower is often developed through a set of disconnected project-level decisions, which miss opportunities to capitalize on system-scale financial value. The HbD approach to project selection—guided by the integration of water-management, energy and financial models—embeds decisions about individual projects within a system optimization, identifying a set of projects that capture those system-level financial efficiencies. This results in a portfolio of individual projects with greater average financial performance than the BaU approach.

Improved management of environmental and social risks: HbD also improves the identification and management of risks to inform site selection. This can reduce the cost and time delays associated with conflict from environmental and social impacts. This results in a portfolio of projects with a lower percentage of significant delays and cost overruns due to environmental and social risks, improving the distribution of projects' NPV compared to the BaU approach.

© BRIDGET BESAW (TOTUMO LAGOON, MAGDALENA RIVER, COLOMBIA)

BOX 7.1
Energy systems by design, revisited

For four days in May of 2016, Portugal's electricity supply came completely from low-carbon renewable sources: solar, wind and hydropower met the country's entire demand for 107 hours.[167] In the month of April 2016, renewables provided 96 percent of generation and, over the course of the year, they contributed to more than half of total generation, a rapid increase from just 16 percent in 2005.[168] This high proportion of renewables, and the ability to run at or near 100 percent renewables for extended periods of time, owes much to the fact that Portugal invested in a great deal of pumped storage as it was simultaneously investing in wind and solar (see photo above).[169] This integration of hydropower with variable sources is also what allows Denmark to meet 42 percent of national demand through wind power, with the grid interconnection to hydropower-dominated Norway providing the necessary supply stability.

Hydropower with storage clearly can contribute to the grid stability needed to integrate a large share of variable renewable energy into a grid. However, peaking or load following from hydropower reservoirs on rivers can result in environmentally damaging rapid fluctuations in flow (see Appendix C and figure C.1). Off-channel pumped storage offers a way to firm up variable renewable sources without negatively impacting rivers. Pumped storage can be built above an existing reservoir, allowing the reservoir, rather than the river, to absorb the flow that fluctuates in response to demand (see photo in Box 2.1). New innovative ideas are being explored for pumped storage, including seawater pumped storage, using the ocean as an essentially infinite lower reservoir and converting an abandoned German coal mine into a 200 MW pumped storage plant,[170] with similar ideas being explored in the United States.

The coupling of variable renewables and strategic hydropower storage, as was done in Portugal, will be crucial for ensuring the reliability and stability of future energy systems based on renewables, but more will be required to make sure these systems are truly sustainable. For that, the principles and approaches of integrated planning explored in this report can be expanded to bring environmental and social sustainability fully into this planning from the earliest stages. Analyses of various alternative mixes of generation sources (e.g., through capacity expansion models) can be coupled with analyses of how those mixes would perform in terms of ecosystems, both terrestrial[171] and freshwater, and their value to people. This integrative—and likely iterative—approach could help identify future investment and management options that will perform well for both energy systems and ecosystems.

167 Neslen, 2016.
168 Energiewende Team, 2016.
169 Ramos, et al., 2014.
170 Parkin, 2017.
171 Kiesecker, et al., 2010.

Feasible to implement

Countries facing urgent demands to increase electricity generation are understandably hesitant to embark on a strategic planning process if they believe it will delay delivery of projects that can meet rising demand. By drawing on new modeling tools and promoting a process that brings together diverse objectives, data sources and families of models, Hydropower by Design can deliver useful insights about development and management options in a relatively short period of time. Rather than delaying decisions or investments, these system-level tools and approaches may reduce project-level uncertainty and delay, thereby lowering investment risk. The financial benefits discussed above effectively provide a buffer which countries can use to pay for decisions that provide broader benefits or reduce environmental or social impacts.

Several of the case studies demonstrated tradeoff analyses that can relatively quickly compare a huge number of investment options and identify those that have the potential for high performance across multiple objectives. This narrowed pool of options could then be studied in more detail. The Magdalena case study showed that project-level financial assessment could be integrated into this approach to give more insight on the financial performance of projects and systems. These approaches could certainly be adapted to quickly inform decisions about options to meet immediate and short-term demands. For example, tradeoff analysis could provide insight into feasible options for improved performance across a range of values for projects that are in the immediate pipeline, albeit options will generally be more constrained the further along a project is. To inform selection of the next project to meet short-term demands, HbD methods could also be adapted to quickly screen for potential "no or low regrets" projects—meaning projects that are likely to be consistent with a broader strategic plan for the system. Thus, modified versions of HbD could be applied to quickly inform actions that meet short-term needs, while more comprehensive strategic planning could then be applied to identify longer-term options.

Hydropower by Design is not an entirely new process, but rather its principles and tools can be integrated into existing planning and regulatory processes. These include options assessments, basin master plans, risk screening, Strategic Environmental Assessment and licensing and mitigation policies. Project preparation facilities, which typically focus on midstream project preparation, could be refined to also promote upstream early planning.

Although this report focuses on hydropower, its essential intent is about much more. Ultimately, this business case is about solving the intertwined challenges raised at the beginning of this chapter: how can the world simultaneously achieve goals for a stable climate, sufficient energy to support prosperous societies and healthy ecosystems? The solutions in this report address a portion of what will be needed to reach those goals.

In closing, we revisit this report's fundamental assertion that expanding the scale of decision making is crucial for achieving more balanced outcomes. Many of the case studies focused on the benefits of moving from single dams toward systems of dams., but the logic of expanding the scale of decision making can be carried further. In a few case studies we demonstrated that expanding the system to include floodplain management opened up broader benefits from reservoirs and improved environmental performance. The Sarawak case study showed that expanding the frame of analysis to include other generation sources could also reveal alternative options for meeting energy needs, with results that highlight the benefits of a generation system that combined large hydropower with decentralized and renewable sources of generation.

This continued expansion in the scale of problem-solving and solution-finding is crucial for meeting the three intertwined challenges and the key to navigating through their associated conundrums (Box 7.1). Ultimately, the search for lower-impact and higher-performing hydropower systems needs to evolve toward the search for lower-impact and higher-performing energy systems. Making this a reality will require its advocates to demonstrate that problem-solving that is integrated and comprehensive can also be feasible and can deliver economic and financial values. Thus, making the business case will continue to be critically important for achieving that sustainable future.

APPENDICES

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Appendix A: A framework for implementing Hydropower by Design for planning

It is now broadly recognized—by conservation organizations,[172] industry leaders (e.g., the early stage of the Hydropower Sustainability Assessment Protocol[173] described in Chapter 6) and funders[174]—that achieving balance between hydropower and other objectives and values can best be achieved by planning and management at basin to regional scales. Project-scale development or management is much more likely to involve zero-sum tradeoffs, while the system scale offers an expanded set of potential solutions and a greater likelihood of achieving "win, win" or "close-to-win, close-to-win" outcomes that provide a broader range of benefits. This report focuses on the potential improvement to economic, financial, environmental and social values that can be achieved through system-scale planning and management.

In this report, we use the term "Hydropower by Design" to indicate the process to find these solutions with broader benefits. This Appendix provides more detail on Hydropower by Design (HbD) as a process and describes its key components. Appendix B is a case study that demonstrates how HbD has been applied in the Magdalena River basin of Colombia.

Hydropower by Design Overview

As noted in Chapter 1, HbD is framework that synthesizes best practices for sustainable hydropower at both the project and system scale. We reiterate that our use of the phrase "by design" does not imply that the hydropower sector fails to incorporate rigorous design. However, under current practices within the sector, design is often limited to narrow spatial scales (e.g., a project) and is not well integrated with planning and design at other scales or with other sectors. Thus, we use the name Hydropower by Design as an overarching term to emphasize that design can be comprehensive (fully integrating other sectors and environmental and social resources) and multi-scale (from project to cascade to river basin to energy system). As illustrated by the case studies in this report (Chapter 5), HbD can be applied across the full lifecycle of dams—from early planning to operation to strategic decommissioning.

Recommendations for system-scale approaches are not new and risk being perceived as complicated or burdensome, slowing the pace of investment in places with urgent need for infrastructure. Thus, throughout this report, we sought to demonstrate that HbD provides economic benefits to countries and is financially viable and feasible to implement.

Economic benefits. HbD can be implemented in ways that will often lead to greater performance for water-management services (such as irrigation, flood management and water supply) along with improved performance for a range of environmental and social values (Chapters 4 and 5).

Financially viable. By capturing value from system optimization and improved risk management, projects developed through and HbD approach can have comparable or superior financial performance (Chapter 4 and the Magdalena case study in Chapter 5).

Feasible to implement. New computational tools allow for relatively rapid comparison of alternatives and screening for options (see case studies in Chapter 5). Integration of different families of models facilitates analyses that simultaneously address the needs of a range of agencies and stakeholders (Figure 4.1 and Magdalena case study in Chapter 5). These examples demonstrate that HbD can deliver useful results relatively quickly. Further, HbD does not necessarily require new legislation, but its components can be integrated into a range of existing mechanisms, including planning, environmental review, licensing and risk screening (Chapter 6).

Hydropower by Design interweaves methods that are integrated, quantitative, multi-criteria and multi-project to achieve hydropower planning and management that promotes sustainability and optimizes benefits for people.

- **Integrated** because it considers all relevant criteria simultaneously, rather than sequentially. In contrast, most assessments, whether at the project level (EIA) or above the project level (cumulative and strategic environmental assessments), consider environmental and social aspects after technical and financial studies have been completed.
- **Quantitative** rather than qualitative, to increase the rigor of the analysis and the confidence in comparing multiple options.
- **Multi-criteria** because of the multi-faceted positive and negative impacts of hydropower.

172 WWF-International, 2006
173 IHA, 2010
174 ADB , et al., 2010; Ledec and Quintero, 2003

- **Multi-project** (or system scale) because cumulative and synergistic costs and benefits of multiple projects are difficult to predict from a sequence of project-based assessments. A hydropower investment program that offers the broadest range of benefits can generally only be identified at a system scale, rather than project-by-project.

Framework for implementing Hydropower by Design

Because HbD is intended to meet a range of stakeholder objectives and inform decisions, the framework we describe below is as much a social process as it is technical. As such, it is not a cookbook that can be followed step-by-step. Rather, it must be tailored to the social, environmental and policy context in which it is applied. In this section, we describe five major components of HbD, emphasing a few major themes, including the importance of embedding HbD's technical process within decision-making processes as well as the value of transparency and stakeholder engagement. Within the major components, we describe potential steps and methods as examples of how these components can be applied within existing policies and practices. The components below are partially sequential, but not strictly so. For example, stakeholder engagement is listed second, but is not a second step, rather it is a feature that should be incorporated throughout the HbD process (see Figure A1). The examples in this section are most relevant for the planning of regions undergoing new hydropower development, but the basic approach and components can be adapted and applied to other situations, such as evaluating options for reoperating dams in an existing system or prioritizing dams for removal. Further, the actions described below are most relevant for an NGO or stakeholder organization that is seeking to influence hydropower planning and management. As described above, agencies can incorporate the principles of HbD into many existing activities. The text on the components below elaborates on those principles and so can also inform agencies that seek to incorporate HbD into their work (e.g., see example of Colombian agencies in Appendix B).

Ideally, HbD focused on new development is informed by an options assessment for energy and water management objectives (e.g., water supply and flood management). Options assessments compare macro-scale alternatives for meeting these objectives, including assessing the extent to which a dam or a set of dams is the best way to meet given objectives (e.g., various mixes of generation sources; achieving water objectives through increased storage vs. conservation).[175] This process can set broad targets for hydropower generation and other energy and water-management services for a planning area. These targets inform subsequent analyses that compare the tradeoffs associated with meeting various objectives.

The Conservancy is currently developing an online guide for implementing HbD, available later in 2017.

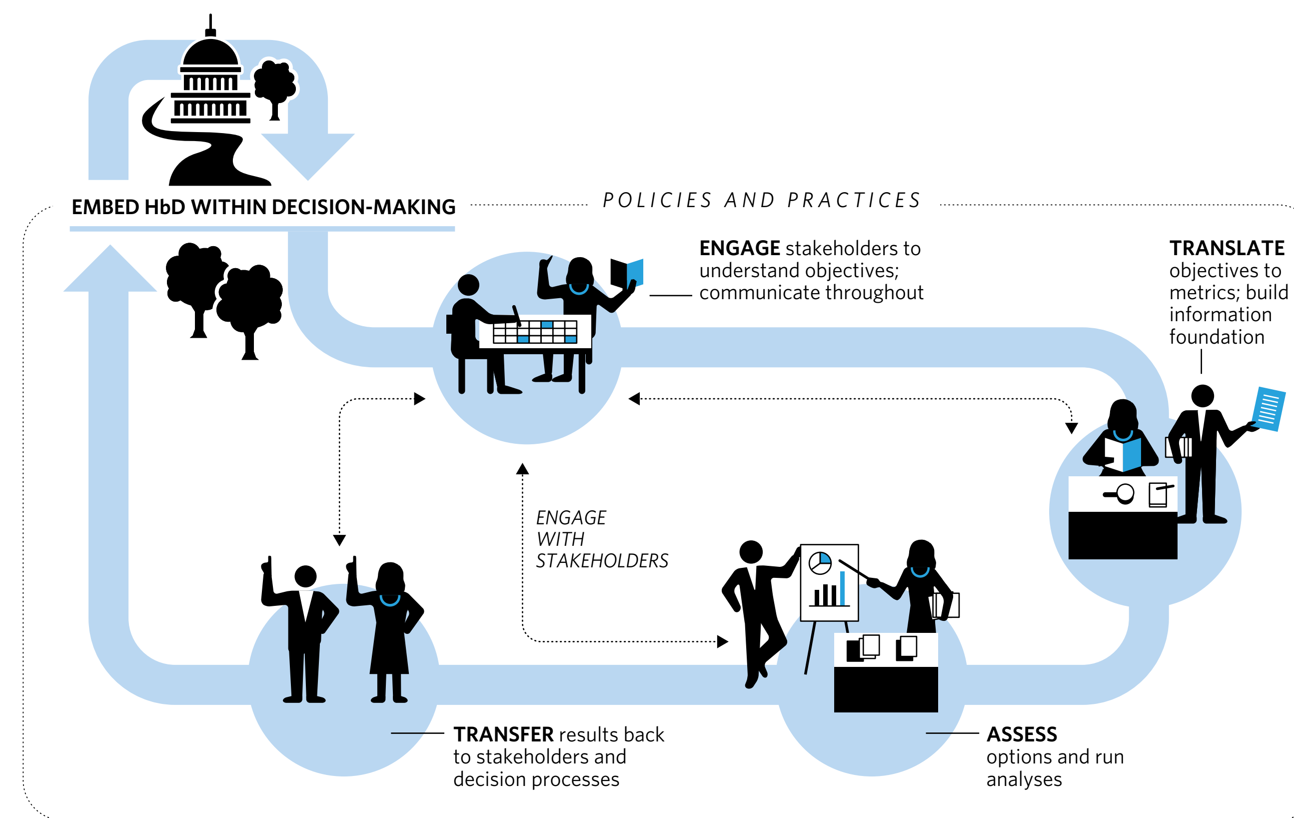
Embed within Planning and Decision-Making Processes. To move beyond modeling studies, applications of HbD should be embedded within a process that can influence decisions (note, however, that modeling studies can indeed have value for educational and training purposes and for persuading agencies and decision makers to try new approaches). Agencies that have decision-making authority (e.g., planners or regulators) can embed the principles of HbD within their processes and practices. Financial institutions can incorporate these principles into their processes to select which projects they fund and what mitigation conditions to apply. Other organizations that seek to implement HbD (e.g., developers or conservation or social advocacy organizations) can encourage decision-making entities to incorporate these principles, through collaboration (e.g., shared studies) or otherwise by ensuring that the information they produce will be useful to those who make decisions (see Appendix B). For example, The Nature Conservancy is working directly with Latin American government agencies and international finance institutions to incorporate various aspects of Hydropower by Design into a pilot for an Early Planning Facility (see Box 6.4), which, if implemented, would support system planning and funding decisions that seek to promote sustainability and minimize impacts and risks.

Engage stakeholders and understand interests and objectives. A primary rationale for Hydropower by Design is to achieve balanced outcomes across multiple objectives. Thus, stakeholder engagement is a critical step for understanding the range of objectives, values and interests in the planning or management region.[176] At key moments throughout the process, a Hydropower by Design application should include opportunities for focused stakeholder engagement. For example, early in the process, stakeholders should be queried about their objectives and values. Through this dialogue, the implementation team can translate a set of objectives that have meaning to people, including communities and the private sector, into metrics that can be measured through analyses. Government objectives—including, but not limited to, those that emerge through options assessments or other planning processes—should

175 WCD, 2000
176 SHARE concept (Branche, 2015) also emphasizes the importance of stakeholder engagement.

FIGURE A1.

A conceptual illustration of the flow of HbD components. Note that we use the term 'stakeholders' broadly to include communities, civil society, developers, operators, and management agencies. Graphically, the figure is intended to convey that the technical and social processes of HbD should be embedded within polices, practices and decision-making processes.



also be formulated as metrics. In addition to early engagement to inform development of metrics, stakeholder engagement will be important throughout the process—e.g., for review of methods, data and results (Figure A1).

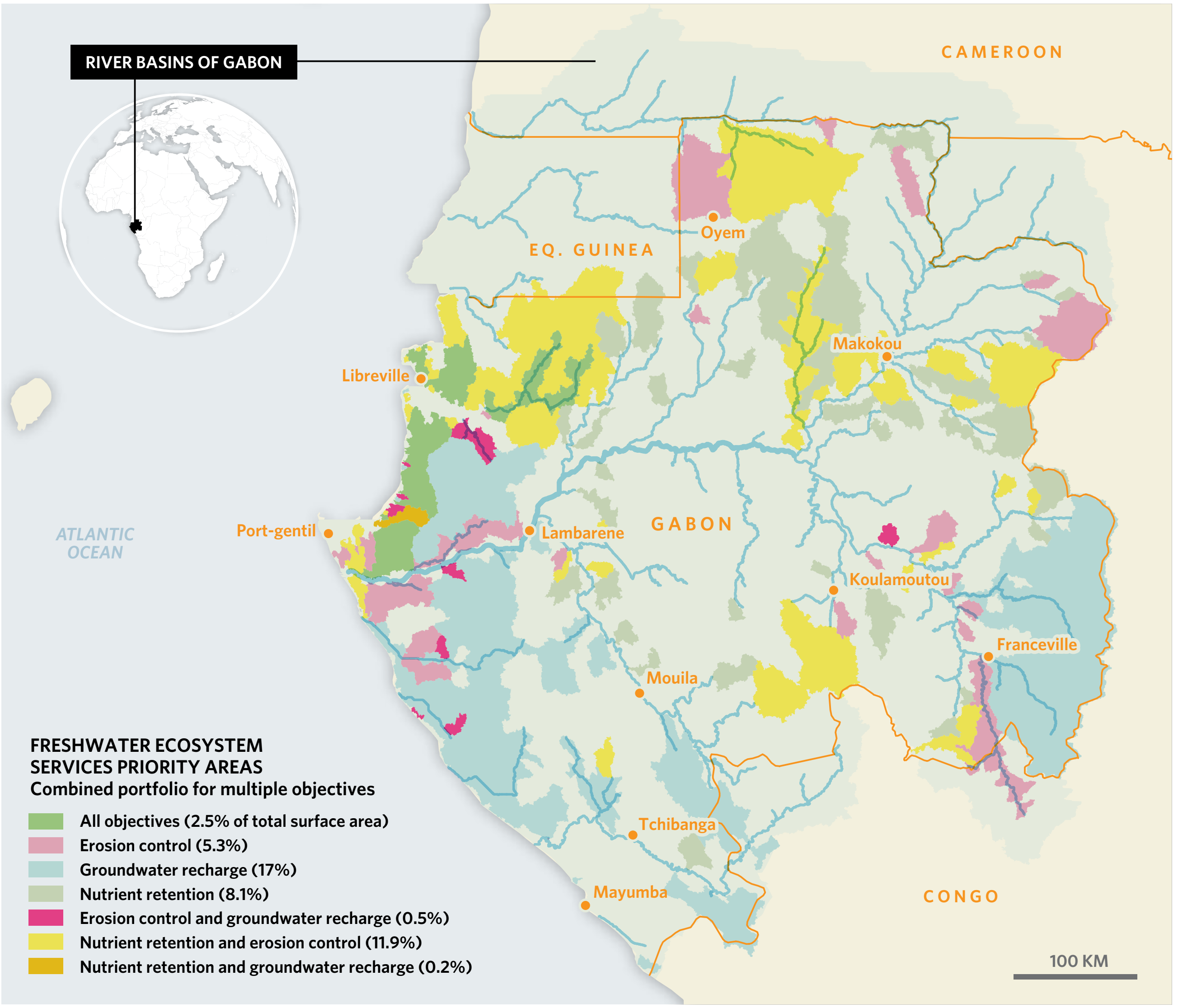
Translate Interests and Objectives into Metrics. The collection of data should be prioritized to underpin the development of the metrics identified through stakeholder engagement. Metrics should be understood by stakeholders as representative of their relevant interests or objectives. In some cases, a stakeholder objective may correspond directly to a quantitative metric (e.g., a flow level desired for navigation), whereas other objectives may require intermediate, composite or proxy metrics. For example, an objective may be the maintenance of farmland in a delta and the implementation team may need to use a metric for sediment transport as a proxy for that objective. Guided by these metrics, the implementation team will collect and organize data into a structure that can support a range of analyses and modeling. The process will generally require collecting a wide range of environmental, biophysical and economic data, including information on existing and potential infrastructure (e.g., data on potential dam sites). Some data may be available through various government agencies or research centers while addressing other information needs may require collection of new data. Environmental and socioeconomic data can be organized and used in a number of different ways in a HbD process (Figure A2).

The case studies in Chapter 5 illustrate the various metrics that can be used. Common metrics include generation, investment costs, flows or storage for irrigation or water supply, as well as environmental and social metrics, such as hectares inundated, people displaced and flow alteration.

Assess Options and Quantify Tradeoff Results. The analytical heart of HbD is a comparison of a (generally) large number of options for developing and managing hydropower projects and systems. Options are compared in terms of how they perform across the metrics developed during stakeholder engagement and data collection and organization. Examples of these analytical methods are provided through the various case studies in Chapter 5, with more detail in Appendix E.

FIGURE A2.

Distribution of ecosystem services in Gabon; ecosystem services (individually or combined in groups) can be used as metrics within a Hydropower by Design process.



Output from the analyses can be used to identify a set of options that are likely to perform well across a range of metrics. However, tradeoffs are often unavoidable and model outputs can also be used to quantify those tradeoffs. Clear visualizations of results are important to ensure that decision makers and stakeholders understand the opportunities and tradeoffs and thus the implications of selecting various options. Figure A3 shows three examples of graphical visualizations of results that can illustrate tradeoffs and help users identify potentially well-balanced options.

Transfer results to stakeholders and decision makers. Results from the tradeoff and other analyses can then be presented to stakeholders and decision makers. As noted above, this dialogue with stakeholders and decision makers ideally occurs throughout the process, not just at the beginning and end. Consistent engagement will allow for interim review and adjustment so that the overall HbD process is transparent and iterative. If the HbD process is well-positioned to influence decisions, the results can then be used to guide official planning, siting decisions, licensing processes and mitigation investments. Appendix B provides a clear example of how HbD tools and information can be tailored to deliver useful results and how those results can be integrated into decision-making processes. In Colombia, a decision-support tool, developed through a HbD program, was designed in part to align with the workflow of a licensing agency. That agency is now using the information provided by that tool to inform its environmental review and licensing decisions.

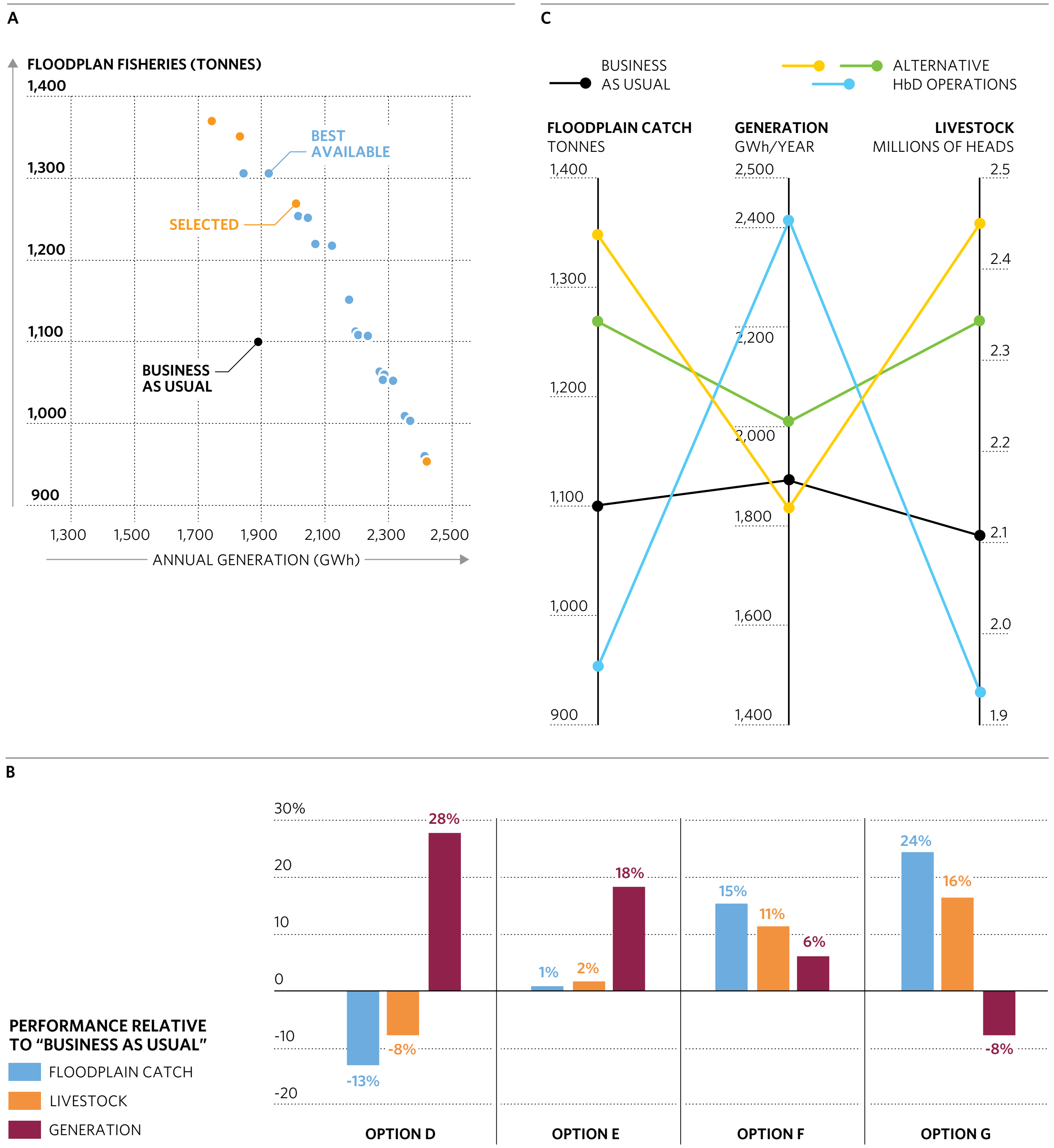
Conclusions

The processes above can be adjusted to accommodate a range of different planning and management contexts and a range of different implementers (i.e., those promoting and pursuing HbD). There are a set of important principles that will be consistent across these different situations.

1. *Ensure that technical work is designed to be relevant and useful to various stakeholders and decision makers.* Data collection and technical tool design should be informed by a clear understanding of what stakeholders and decision makers need.
2. *Comprehensive engagement with stakeholders.* Processes should be transparent and sustained engagement and two-way dialogue with stakeholders will increase trust in results and the durability of decisions that emerge from the process. This engagement will also help ensure that a HbD process is comprehensive in terms of including relevant economic, social and environmental resources.
3. *Through integrated analyses, compare multiple options and look for “win-win” or “close-to-win, close-to-win” options.* HbD applications can integrate diverse models and tools that can produce diverse outputs that make sense to different groups. Comparing multiple options increases the likelihood of identifying options that work well for many objectives or interests.
4. *Decisions are the key.* HbD produces real results when it is linked to decisions of those entities that build or finance dams or those that manage dams and rivers and other resources. This Appendix has focused primarily on a technical framework that includes stakeholder engagement. However, as illustrated in Figure 1a, the entire process takes place within a broader context of policies and decision making: development decisions, funding decisions, regulatory and management decisions. The interaction of HbD with these decisions will generally not be a single step, but rather an iterative interaction, in which decision processes evolve in response to new information and new options, while updated decision processes set the demand for further information and additional options.

FIGURE A3.

Several options for displaying results from a HbD process. (a) For the Tana River, the options to reoperate a cascade of dams show a tradeoff between generation and floodplain fish harvest, with harvest declining as generation increases. However, there are a range of options that perform better for both generation and harvest compared to the BaU option (black dot). In a Pareto-optimal perspective, these options dominate the BaU. The orange dots show the options displayed in Figure A3.b (b) A bar chart showing the performance (in percent) of various HbD options across a range of metrics, relative to BaU. Two options show that improved performance is possible for all three metrics; (c) these options can also be displayed on a parallel plot figure. Each line represents a different option (the BaU option is black). Each vertical axis represents a different performance metric, with its own scale and the performance of an option for that metric is indicated by where the line crosses that axis. Axes are oriented so that better performance is always higher, thus for metrics the model seeks to maximize (e.g., fish harvest) the highest number is at the top; for a metric the model seeks to minimize (such as investment cost; not shown here) the lowest value is at the top. The data in these figures are from the Tana River case study on page 108.



Appendix B: The Magdalena basin in Colombia as an example of implementing the Hydropower by Design framework[172]

Introduction and overview of the Magdalena Basin

The Nature Conservancy's ongoing work in Colombia's Magdalena River basin provides a comprehensive illustration of an application of the Hydropower by Design (HbD) framework described in Appendix A. This case study first reviews the overall context for the HbD program in Colombia, including current and future hydropower in the Magdalena and the basin's other diverse resources. We then describe how the activities, products and objectives of the program correspond to the components of HbD highlighted in Appendix A.

Hydropower in Colombia

Beginning in 2001, Colombia enacted a series of energy reforms and resolutions that established targets for increasing generation from low-carbon and renewable sources. Hydropower is by far the country's largest source of low-carbon energy. As of 2014, Colombia's hydropower system generated nearly 64,000 GWh, representing nearly 70 percent of total generation in the country, from an aggregate installed hydropower capacity of 11 GW.[173] The majority of Colombia's hydropower (60 percent) is within the Magdalena basin and most projected expansion will also occur in the basin.[174] The Magdalena basin currently has 35 hydropower dams with a combined capacity of 6,673 MW. A national inventory in the 1970s identified another 100 potential sites for hydropower development with an aggregate capacity of over 24,000 MW.[175] Two large dams, with a total capacity of 2,800 MW, are currently under construction in the basin.

Though most of the hydropower dams (existing and potential) are single purpose, other water-management objectives, such as flood management, can influence dam planning and operation. For examples, proposals for a series of dams on the mainstem Magdalena are driven largely by navigation objectives, though these lock-and-dam structures would likely also generate hydropower.

The Magdalena River basin and its resources

The Magdalena is the fifth largest river in South America, with a 1,500 kilometer mainstem and a mean annual flow of 7,200 cubic meters per second at its mouth. The Magdalena basin forms the economic, social and cultural heart of Colombia. It covers 24 percent of national territory (274,000 square kilometeres) and 36 million people reside there. Due to this concentration of population and its abundant natural resources, the basin produces 86 percent of the country's gross domestic product and 75 percent of its agricultural production.

The Magdalena basin also supports high levels of species diversity, in part due to the great variety of habitats it contains, ranging from the glaciers at the river's headwaters in the Andes Mountains to the dry tropics where the river flows into the Caribbean Sea. Those habitats support over 250 species of mammals, 800 species of birds, 400 species of amphibians and more than 200 species of fish, of which more than half are endemic.

Historically, the Magdalena supported Colombia's largest freshwater fish harvest, particularly from the massive floodplain wetlands in the lower basin. Average annual harvests have declined by 50 percent between 1977 and 2010 due to a range of factors, including pollution and habitat degradation from mining, deforestation and farming. Dams have fragmented the river network and reduced spawning habitat for migratory fish species. Threats from expansion of hydropower include further fragmentation and changes to the flow regime that could reduce connectivity between the river and the productive floodplain wetlands.

The Magdalena is central to Colombia's food and water security and energy production. Due to its diverse other economic, environmental and cultural values—and the risks to those values during development of resources—the national government has prioritized sustainable management of the basin as a national economic priority.

172 Written with contributions from Rebecca Peters, Juliana Delgadao, Hector Andres Angarita Corredor, Carlos Andres Rogeliz Prada and Katie Crossman
173 IHA, 2016.
174 IEA, 2014
175 Study of the Electric Energy Sector, ESEE, 1979

Implementing the Hydropower by Design framework

The Magdalena River basin—and its associated habitats, species and ecosystem services—is one of the top conservation priorities for The Nature Conservancy in Colombia. Due to the projected expansion of hydropower to meet the country's growing energy needs, the Conservancy is focused on working with a set of partners to help the country address those needs in a way that is consistent with a healthy Magdalena River. To do this, the Conservancy began a program in 2008 focused on integrated river basin management for the Magdalena, from which emerged an emphasis on sustainable hydropower and river conservation. Below we outline how this program illustrates an applied implementation of the HbD framework.

Embed within Planning and Decision-Making Processes

Beginning in 2008, the Conservancy began to assemble scientific information to support integrated management of land and water resources in the Magdalena River basin and, at the same time, began to reach out to government agencies to understand how that scientific information could be most useful to guide decisions. The Conservancy also supported refinements to environmental regulation, such as incorporating the mitigation hierarchy and biodiversity compensation into the licensing process.

With its emerging focus on promoting balance between hydropower and conservation, the Conservancy began to work closely with government agencies such as Cormagdalena (the primary agency managing the mainstem Magdalena), the Ministry of Environment and Sustainable Development (MADS) and the National Environmental Licensing Authority (ANLA)—the executive agency responsible for implementing environmental policy related to licensing. The Conservancy worked with MADS in 2010 to develop a framework on environmental flows. Following that, in 2012, the Conservancy began close technical collaboration with ANLA. Through this process, ANLA began adopting elements of HbD, integrating Conservancy modeling tools to identify cumulative basin-level impacts and drawing on principles of HbD to inform environmental license processes. An agreement in late 2016 formalized the Conservancy's role providing technical support for project license evaluations and regional assessments to inform ANLA's activities.

The Conservancy's work to understand how HbD tools and information could inform agency decisions illustrates the value of embedding HbD within decision-making processes. As a result, agencies in Colombia are now incorporating principles of HbD and information from related tools into decision processes that can avoid and minimize impacts from development.

Engage stakeholders and understand interests and objectives

To support its HbD work—and to inform decision processes—the Conservancy developed a suite of information resources and a decision support tool called SIMA,[181] which can be used to guide decisions about hydropower and river conservation (described further in the next section). To build these resources and ensure they were addressing the most important issues, the Conservancy sought to understand the interests and objectives of a broad range of stakeholders. The Conservancy met with national agencies, regional environmental authorities of the Antioquia region (Conare and Corantioquia) and private industry groups such as Acolgen, Medellin Public Enterprises (EPM), Celsia and Isagen. Through this engagement, the Conservancy developed a stronger understanding of the types of environmental processes and social resources that should be built into the models and databases. This understanding is reflected in the environmental and social metrics that were used in the Magdalena case study in Chapter 5. The meetings with industry groups informed the modeling of hydropower decision-making, also discussed in the Magdalena case study.

Translate Interests and Objectives into Metrics

Colombia is fortunate to have a relatively high level of data availability, with detailed information on topography, climate and hydrology at both the basin level and for specific sub-regions. Drawing on these data and a series of expert workshops, the Conservancy developed a Conservation Blueprint, in collaboration with Cormagdalena, which identified priorities for conservation in the basin.[182] However, the Blueprint gained minor influence with decision makers because, on its own, it provided limited ability to evaluate cumulative impacts at the level needed.

To meet those needs, the Conservancy worked with a group of partners, including the Stockholm Environmental Institute (SEI) and Colombian universities, to develop a water-management model more tailored to decision-making processes. This resulted in a set of customized applications of SEI's Water Evaluation and Planning System (WEAP) for the Magdalena, such as the integration of the Conservancy's Indicators of Hydrologic Alteration. The Conservancy then worked with partners to combine these WEAP applications with the Conservation Blueprint and other resources, such as the Conservancy's Barrier Analysis Tool (BAT),[183] into SIMA.[184]

SIMA translates different stakeholder interests into a format useful for decision makers and project developers to examine different options, such as a proposed hydropower project or multiple proposed projects, to better understand potential impacts on environmental, social and cultural resources. Because it is designed as a basin-scale modeling tool, SIMA can go further than traditional project-level impact analysis to better understand cumulative impacts. SIMA can also be used to compare the outcomes associated with basin-level development trajectories, as described in the Magdalena case study, allowing stakeholders and decision makers to look beyond single projects and to envision how planning decisions can lead to different long-term and large-scale outcomes. For instance, using IPCC climate data, users can model the performance of alternative hydropower development options under different scenarios of future climate and hydrology.

To promote its uptake, SIMA was designed to integrate with the workflow of users such as ANLA. Further, by allowing all users access to the same information, SIMA supports transparent decision-making and gives stakeholders the ability to assess the outcomes of different decisions. Before the launch of this interactive software tool, this type of information access required physically convening people around the table. Now, SIMA can play the role of the table in a virtual environment for users to learn and exchange ideas and results. Launched in March 2017, SIMA is now a publicly available tool able to engage wider audiences.[185]

Building on SIMA's foundation, the Conservancy and a range of partners—including MADS, ANLA, Conare, Acolgen and the Colombian Institute for Hydrology and Meteorology—formed the Collaborative Partnership, a group focused on collective knowledge development and information sharing. In December 2016, the Partnership began to develop additional tools for early planning and data management. The Partnership also discussed ways to overcome barriers to implementation of the national offset scheme (described in Chapter 6). By working with the Partnership, the Conservancy can continue to improve scientific understanding of basin processes and translate interests into effective metrics.

Assess Options and Quantify Tradeoff Results

As described above, SIMA is intended to assess development options and to help decision makers and stakeholders understand the impacts and tradeoffs of different decision. To quantitatively examine basin-scale options and tradeoffs in greater detail, in 2016 the Conservancy began collaborating with PSR, a global provider of modeling and optimization tools and consulting services for hydropower. This partnership focused on testing the underlying hypothesis of HbD: that a comprehensive planning approach considering environmental, social and multi-use dimensions of hydropower can demonstrate similar or better financial and economic outcomes relative to a business-as-usual approach. The collaboration utilized PSR's models to simulate alternative scenarios of hydropower development for the Magdalena basin, producing results for generation and financial returns for a selected expansion plan. The research relied on interactive feedback between PSR's models and the Conservancy's models and data—such as using data on environmental and social impacts to inform PSR's financial analysis of the costs of delays due to those impacts. The various scenarios developed through PSR's tools were also exported into SIMA to quantify and compare cumulative impacts.

The results of these analyses are the focus of the Magdalena case study in Chapter 5.

Transfer results to stakeholders and decision

As described above, SIMA was specifically designed to provide useful information to ANLA and other decision makers and stakeholders. To evaluate applications for licenses (e.g., from a hydropower dam), ANLA relies on the information developed through Environmental Impact Analysis. Recently, ANLA has begun to complement that information with outputs from SIMA, which can provide information often not available at the project level, such as insights about cumulative impacts. The collaborative work with PSR will deliver the type of information that will not only help agencies understand and avoid impacts, but also help decision makers develop long-range plans about which projects will deliver the most benefits to the country.

181 Acronym for Sistema de Información para la toma de decisiones en la Macrocuenca Magdalena-Cauca
182 TNC, Magdalena Conservation Blueprint.
183 Barrier Analysis Tool (BAT) - https://www.geodata.soton.ac.uk/geodata/gis/project173
184 The project was jointly funded by Fundación Mario Santo Domingo, USAID and IKI, with support for policy and stakeholder engagement coming from the MacArthur Foundation.
185 http://www.sima-magdalena.co/

Key points and lessons learned

The application of HbD in the Magdalena basin demonstrates that collaboration with a range of partners—including governmental agencies, research institutions, basin communities and other NGOs—greatly strengthens the relevance and positive impact of the approach. Sustained engagement with multiple stakeholders allowed the Conservancy to develop tools such as SIMA to improve the capacity of government and research institutions and has created new opportunities for interaction between various groups. By demonstrating it could deliver useful information through tools informed by a dialogue with stakeholders, the Conservancy was able to integrate elements of the HbD process into hydropower planning and licensing for the Madgalena basin. In the future, the Conservancy will use SIMA to increase stakeholder access to information and improve their ability to inform and influence decision-making processes. Through rigorous interdisciplinary analysis, demonstration projects and forward-looking collaboration with diverse partners, the Conservancy will continue to support system-scale planning for energy that acknowledges the connections between conservation, the economy and human well-being.

Appendix C: Impacts of hydropower on the environmental and social resources of rivers

Rivers and associated ecosystems—including floodplains, estuaries and deltas—are among the most productive and diverse ecosystems on the planet, supporting the greatest value of ecosystem services per unit area.[177] Further, river valleys generally support the highest value agricultural land along with towns and cities. The dams required to generate hydropower unavoidably change rivers and river valleys and thus, in addition to development benefits, hydropower can also cause significant social and environmental impacts. Freshwater species and populations are declining at rates higher than those of terrestrial and marine ecosystems[178] and, in regions of the world with high levels of development, water management infrastructure, such as dams, consistently rank among the leading causes of decline of freshwater-dependent species.[179]

The environmental and social impacts of hydropower projects have been described thoroughly elsewhere[180] and thus we present a relatively brief summary here. While impacts can be divided into environmental and social categories, these categories are highly intertwined. For example, the loss of floodplain inundation affects both fish populations and human communities dependent on floodplain fisheries. Here, we organize impacts into those affecting upstream resources, connectivity and downstream resources.

Impacts to upstream resources

The impacts to upstream resources have generally received the most attention in debates about dam development. Dams to provide storage can create very large reservoirs that inundate upstream land, including communities, roads and other infrastructure, agricultural land and ecosystems. The displacement of communities by a reservoir often generates the most controversy over dam development. For example, construction of the Three Gorges Dam on the Yangtze River in China required the relocation of approximately 1.5 million people.[181] The World Commission on Dams estimated that 40 to 80 million people had been displaced by dams. That estimate was as of the year 2000 and so that number has grown.[182] Those displaced by dams are often poor and lack political strength. A survey of resettlement programs found that living standards declined for the majority of those resettled in 36 out of 44 cases reviewed (82 percent).[183]

Reservoirs replace the flowing, dynamic and variable aquatic habitat of a length of river by a flatwater lake with habitat features that favor a different suite of organisms, such as reservoir-adapted fish replacing riverine fish. Often, the change from river to reservoir results in a replacement of endemic and/or rare species (e.g., the endemic fish fauna of the Colorado River in the southwestern USA) with common and widespread "generalist" species—often non-native and invasive—such as bass or tilapia. Conversion of rivers to reservoirs can result in extinctions, such as the loss of 34 species of freshwater snail following construction of seven hydropower reservoirs on the Coosa River in Alabama (USA).[184]

Impacts to connectivity

Dams and reservoirs affect the downstream transport of sediment, wood and nutrients and disrupt the upstream and downstream movement of organisms, including fish and invertebrates.[185] Dams can either be complete or partial barriers: in some cases fish-passage facilities can allow some passage to continue, particularly with relatively low dams and for fish species that are strong swimmers and/or jumpers. However, many fish passage facilities have very low passage effectiveness and/or may be impassable at some flow levels. Further, fish passage may work effectively for upstream movement, but not for downstream movement.[186] In addition to the barrier of the dam wall itself, hydropower projects can disrupt longitudinal hydrological connectivity within a river by dramatically changing hydrological conditions upstream and downstream of the dam. Some hydropower dams divert most or all of a river into a canal, leaving a bypass reach with little or no downstream flow. Large storage projects can create a long lake-like reservoir with little or no current and this reservoir can function as a barrier to the downstream movement of aquatic organisms and to

177 Costanza, et al., 1997
178 WWF 2015; Ricciardi and Rasmussen 1999
179 Richter, et al., 1997; McDonald, et al., 2012; Reidy, et al., 2012
180 Postel and Richter, 2003; World Commission on Dams, 2000
181 Heggelund, 2006.
182 World Commission on Dams, 2000.
183 Scudder, 2005.
184 Johnson, et al., 2013; Conservation Status of Freshwater Gastropods of Canada and the United States
185 March, et al., 2003
186 NRC 1996

the migration of terrestrial organisms across the river. Migratory fish can be particularly affected by dams that act as barriers to and from spawning habitats and, because migratory fish can be dominant within fish harvests, their loss can have major negative impacts on communities that depend on river fisheries.

As a river enters a large reservoir, flow velocity can decrease toward zero and the river no longer has sufficient energy to transport much of its sediment load. Sediment sizes such as gravel and sand drop out relatively quickly, forming a delta where the river enters the reservoir. In addition to reducing the storage volume and longevity of a reservoir, this sediment-trapping function can have serious impacts on the downstream river, described below.[196] Water quality conditions within reservoirs can result in elevated levels of methyl mercury in water and biota, making this dangerous contaminant available throughout the food chain, posing health risks to humans consuming fish from reservoirs.[197]

Impacts to downstream resources

While traditionally receiving less attention than the upstream resources affected by impoundment, dam impacts to downstream environmental resources are often far greater than the upstream impacts. Because human livelihoods and communities are often directly tied to functioning river ecosystems, these downstream environmental impacts can also have considerable social costs.[198]

As described above, large reservoirs can trap nearly all sediment, except for the smallest particle sizes and even small reservoirs can trap much of the larger sediment in transport (e.g., cobbles and gravels). Globally, reservoirs trap about a quarter of sediment in transport, resulting in a net reduction in the delivery of sediment from watersheds to oceans of 1.4 billion tons per year, compared to levels before people began modifying landscapes and rivers. The cumulative storage of sediment in reservoirs is approximately 100 billion tons.[199] This trapping disrupts the balance of erosion and sedimentation downstream, contributing to degradation of the river bed (incision), which can isolate the river from its floodplain and bed armoring, whereby smaller sediment sizes are entrained leaving behind only large, immobile cobbles and boulders.[200] Because sediment also transports key nutrients, in addition to altering downstream physical habitat, sediment trapping also reduces nutrient availability to downstream food webs, negatively impacting the productivity of fisheries. Finally, the retention of sediment within reservoirs deprives downstream deltas of the material they need to keep pace with erosion, compaction and rising sea levels. Dams are one of the leading cause of the shrinking of deltas worldwide. Deltas are home to over 500 million people (one out of every 12 people on earth) and support some of the most productive fish harvests and agriculture. For example, the rapidly receding Mekong delta supports half of the rice crop of Vietnam, the top global exporter of rice.[201] Full buildout of proposed hydropower dams in the Mekong basin would capture nearly all sediment in transport, exacerbating the shrinking of its delta.[202]

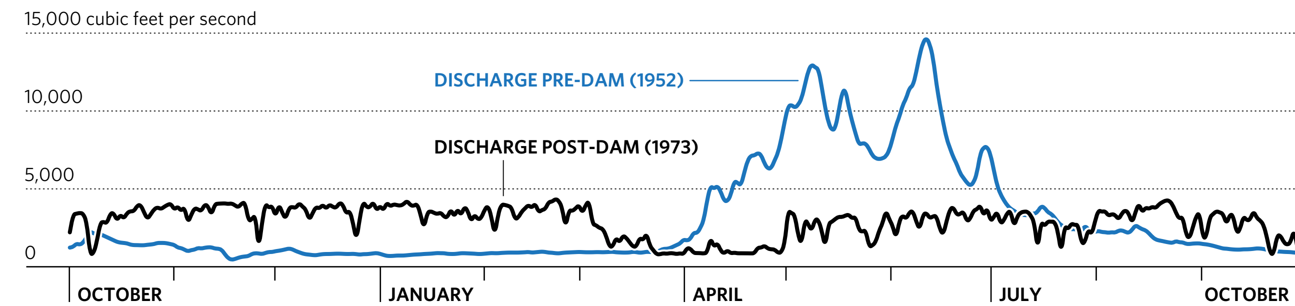
Reservoirs capable of storing a large volume of water can significantly alter the flow regime downstream of a dam (Figure C1). The flow regime can be viewed as a master variable that structures river ecosystems—affecting channel morphology, water quality and ecological processes—and thus disruptions to the flow regime can have serious consequences for river ecosystems. For example, fish behaviors for reproduction and migration are often triggered by changes in the flow regime, such as floods and so dam-induced changes to the magnitude, timing, or frequency of flood events can therefore depress fish populations.[203] Hydrological alteration, largely caused by dams, is one of the primary threats to freshwater ecosystems and their species, which are imperiled at rates that exceed those of terrestrial and marine ecosystems.[204] The recent Living Planet Index from WWF reported that populations of freshwater vertebrate species have declined by nearly 80 percent since the 1970s, a rate of decline that is twice that of vertebrate populations on land or in the ocean.[205]

As described earlier, the operation of hydroelectric dams to meet peak power demands results in extreme daily fluctuations in flow (Figure C1). The high flows can lead to catastrophic drift (rapid downstream transport) of invertebrates, displacement of fish and channel degradation.[206] Sudden declines in flow can beach fish and the no- or low-flow interval between periods of

196 Baran, et al., 2015; http://www.worldfishcenter.org/content/fish-sediment-and-dams-mekong
197 Tremblay and Lucotte, 1997. Accumulation of total mercury and methyl mercury in insect larvae of hydroelectric reservoirs. Can. J. Fish. Aquat. Sci. 54: 832.841
198 Richter, et al., 2010
199 Syvitski, et al., 2005.
200 Ligon, et al., 1995.
201 Syvitski, et al., 2009.
202 Kondolf, et al., 2014.
203 Poff, et al., 1997.
204 Postel and Richter, 2003
205 WWF, 2016.
206 Kennedy, et al., 2016.

FIGURE C1.

Annual hydrographs on the Green River (Utah, USA) before (blue) and after Flaming Gorge Dam (black). The managed hydrograph illustrate two primary ways that reservoir operations can alter downstream flow regimes: one, changes to major components of the hydrograph, including the loss of the flood peak (April through July) and elevated low flows (October through March); two, dramatic daily to weekly fluctuations as dam releases through the turbines respond to changes in electricity demand (i.e., due to load following or peaking).



generation can also strand aquatic organisms within isolated pools, where they become vulnerable to high temperatures, low dissolved oxygen and predation. The effects of peaking may persist for long distances downstream below a dam.[207] Hydropower dams that divert water into a tunnel or canal result in a bypass reach in between the diversion and return points (though note some diversions can export the water to another river system). In some cases, the bypass reach can be nearly, or completely, dewatered.

In addition to changing the flow and sediment regimes, dams can also alter the water quality of water that is discharged from the reservoir into the river. For example, dams that discharge from the bottom of the reservoir typically release water that is colder than river water, while discharge from the reservoir surface can be warmer than the river (a phenomena referred to as “thermal pollution”), potentially contributing to changes in the fish fauna.[208] Dams on the Murray River in Australia reduce water temperatures 12°C below natural levels, preventing the spawning of native fish whose reproductive physiology requires warmer temperatures. Reduced temperatures persist for 300 kilometers downstream.[209] Reservoirs can also release water that is low in dissolved oxygen or has other water quality problems.[210]

These environmental impacts can translate to social impacts on communities downstream of dams such as declines in fisheries and flood-recession agriculture. Richter, et al.,[211] suggested that a greater number of people may have been impacted by changes to flow regimes from upstream dams than the number of people directly displaced by dams. For example, hundreds of millions of people around the world depend on the productivity of large-river floodplains and this productivity is driven by the natural flow regime—particularly the seasonal inundation of vast and productive floodplain habitats. Rivers that exhibit annual flood pulses onto extensive floodplains have significantly higher productivity of fish than waterbodies per unit area, including rivers or reservoirs, that lack a dynamic flood pulse, a phenomenon characterized as the “flood-pulse advantage.”[212] The Mekong River supports the largest freshwater fishery in the world and its productivity is derived from the extensive floodplains and lakes inundated by the annual flood pulse. Tens of millions of people derive their primary source of protein from the fish harvest. Annual harvest from the Mekong River is over two million tons (see case study in Chapter 5). By altering the flow regime, dam management can negatively impact the productivity of downstream river-floodplain systems. Further, many of the fish harvested within floodplains, deltas and estuaries have migratory life histories, dams that fragment connectivity with upstream habitats used for spawning can also affect productivity in these downstream habitats.

207 Freeman, et al., 2001.
208 Olden and Naiman 2010.
209 Sherman, et al., 2007
210 Fearnside, 2005.
211 Richter, et al., 2010.
212 Bayley, 1991.

Past dam development has been associated with dramatic declines in populations of migratory fish on rivers such as the Columbia (Washington, USA), Penobscot (Maine, USA) and Rhine (Europe). In many cases, dam development occurred during periods when several other environmental impacts were occurring, including overfishing, pollution, loss of habitat (e.g., levees to disconnect floodplains) and widespread land-use conversion in river basins. A recent study from the Mekong basin used fish population models to estimate the impacts to migratory fish—which represent the majority of the capture fish harvest—from building dams on the mainstem of the river, finding that full buildout could cause the loss of up to half of the biomass of migratory fish (see Figure 5.2).[213]

213 ICEM, 2011.

Appendix D: Hydropower by Design and Climate Change[186]

Changing climatic conditions, including changing patterns of precipitation, runoff and evaporation, will very likely affect hydropower operations in many parts of the world. The system planning advocated in this report can increase the resiliency of hydropower to these changes, providing further support for the business case for Hydropower by Design.

Models of future climate under increased greenhouse gas levels consistently predict higher average temperatures, but the models tend to have greater uncertainty with hydrology. There is general agreement that some currently wet regions of the world will get wetter and some dry regions will become drier.[187] Scientists also generally concur that hydrographs may become flashier—experiencing greater frequency and intensity of both floods and droughts.[188] Recent trends suggest that precipitation patterns have already changed. For example, the frequency of intense storms (greater than 7.5 centimeteres of rain in one day) has approximately doubled, compared to 50 years ago, in the United States Midwest.[189]

Some hydrological changes are directly linked to changes in temperature and so can be predicted with greater certainty. In general, because of rising temperatures, evaporation will increase, reducing water availability, even with unchanged precipitation. Changes in temperature can also produce seasonal shifts in runoff due to an increase in rain relative to snow, shifting a portion of runoff from the snowmelt period to the rainfall period.[190] Further, snowmelt and glacier melt will tend to begin and end earlier in the year.[191]

These hydrological changes will affect the viability of existing and future hydropower projects and complicate calculations on expected generation from new projects. The World Commission on Dams summarized a set of risks to hydropower from climate change, including:

1. *Reduced inflow*, due to changes in precipitation, evaporation and water use in the upstream watershed.
2. *Risks from higher magnitude floods.* If projects do not accurately account for potential increases in flood magnitude then the project risks being under-designed for resisting floods, increasing the risk of dam failure. Larger floods also increase the likelihood of emergency releases that can pose a danger to downstream communities and a greater probability of spills.
3. *More conflicts with other demands* within multipurpose reservoirs due to less water or less certainty. Examples include flood management and the ability of a reservoir to provide downstream environmental flows.
4. *Greater evaporation from reservoirs*
5. *Increased sedimentation*

Over the short term, higher rates of glacial melt will increase the availability of water for hydropower for projects below glaciers. For example, 2003 was one of the hottest and driest years in Switzerland in the past 500 years. Despite lower precipitation, Swiss hydropower production was only 0.8 percent below the 10-year average due to significant glacial loss. However, over the long term the decline of snowpack and glaciers will result in a decline in generation for projects that previously depended on meltwater. Climate change will also likely lead to increases in evaporation from reservoirs, which can be significant in arid areas, such as the Zambezi where, currently, approximately 16 percent of the river's mean annual flow is lost to evaporation from reservoirs, resulting in hydropower being the single biggest consumer of water in the basin.[192]

186 Adapted from: Opperman, et al., 2015b.
187 Durack, et al., 2012.
188 Kundzewicz, et al., 2008.
189 Saunders, et al., 2012.
190 Gleick and Chalecki, 1999.
191 Barnett, et al., 2005.
192 SADC-WD and Authority, 2008.

Hamududu and Killingtveit[221] conducted a global analysis of how climate change will affect hydropower, using runoff as the main determinant to generation. At the continental scale, the effect of climate-altered hydrology on hydropower was relatively small, in part due to offsetting increases and decreases in generation in different areas. For example, within Africa, projections for hydropower in east Africa increased, while southern and northern decreased. The west stayed about same. Much larger changes were forecast at the scale of individual countries, with hydropower generation in Uganda forecast to increase by 15 percent and generation in Namibia forecast to decrease by 21 percent. Impacts may also be quite significant within individual basins. Climate studies predict a 26 to 40 percent decline in average annual runoff for the Zambezi River basin by 2050, compared to a 1960-1990 baseline. A World Bank study on future management options in the Zambezi basin projected a 32 percent decline in firm energy generation from the Zambezi hydropower system (from 30,000 GWh per year to 20,000 GWh per year) and a 21 percent decline in average energy production (from 56,000 GWh per year to 44,000 GWh per year), due to declining inflows.[222]

In general, run-of-river projects will be more vulnerable to hydrological changes than storage reservoirs and projects that rely on snowmelt will also be more vulnerable. For example, Connel-Buck, et al., found that low elevation reservoirs in California, that have storage, will see declines of 4.5 percent in hydropower generation.[223] In comparison, Madani and Lund found that California's high-elevation hydropower system—which are generally run-of-river dams with limited storage and depending on the snowpack—would experience a 14 percent decline in generation.[224]

Countries that have a high reliance for hydropower for their electricity supply can be vulnerable to droughts and this vulnerability may increase due to climate change.[225] Regionally, southern Africa is 60 percent dependent on hydropower for their electricity and this region is already vulnerable to droughts and is forecasted to become drier with a greater frequency of droughts.[226]

The changes in temperature and precipitation will also affect the various other water-management services described in Chapter 2, potentially increasing competition between various uses for water within multipurpose reservoirs and water-management systems.[227] Reduced discharge and increased evaporation will lessen supply for irrigation while higher temperatures will increase demand for irrigation water through increased evapotranspiration. Some previously rainfed agricultural land may require irrigation to remain productive. Flood managers will seek greater storage allocation to flood management due to increased flood risk while water-supply managers will seek increased allocation to storage to manage for increased drought risk. For example, in the Zambezi River, water managers will confront tradeoffs between maximizing head for hydropower (with high reservoir levels) and leaving empty storage to attenuate floods.[228]

Reservoir management will also see competition between storage for firm hydropower and the release of environmental flows, such as for salmon in the Columbia River.[229] Climate change could degrade habitat for temperature-sensitive species like salmon[230] and declines in population of species could result in new requirements for mitigation to avoid extinction. Temperature-sensitive species will generally migrate to cooler portions of the river network, but dams may act as barriers to this movement.[231] Interestingly, for some temperature-sensitive species, flow management from dams may promote regional persistence in areas undergoing climate change. For example, Yates, et al., also forecasted that Shasta Dam can maintain a cold pool of water to support flows of the appropriate temperature to support spawning and rearing habitat for salmon in the Sacramento River assuming a mid-century warming of 2°C, although the reservoir may not be able to maintain a cold pool if warming reaches 4°C.

Changes to other water-management sectors, along with impacts on species' viability, will affect the economics of hydropower projects. Increased demand for other uses of water may reduce the financial viability of hydropower within multipurpose projects, or environmental requirements may reduce the financial viability of single purpose hydropower dams.

221 Hamududu and Killingtveit, 2012.
222 World bank 2010.
223 Connel-Buck, et al., 2011.
224 Madani and Lund, 2009
225 Ebinger and Vergara, 2011; Matthews, et al., 2011
226 Beilfuss, 2012.
227 Lee, et al., 2009.
228 Beilfuss, 2012.
229 Payne, et al., 2004.
230 Yates, et al., 2008.
231 Palmer, et al., 2008.

Thus, for a variety of reasons, the system-scale approach to planning and management described in this report will become even more important due to changing climatic conditions. To increase the resiliency to climate change of river basins and infrastructure investments, applications of Hydropower by Design should incorporate scenarios with a range of future hydrologies and demands on other water-management systems and stressors on ecosystems. These different assumptions of conditions and drivers could certainly result in the identification of different solutions for dam siting, design and operation and also influence how conservation priorities are identified. For example, the tradeoff analysis described in several of the case studies was applied in the Koshi River basin in Nepal, using a range of potential hydrologies to identify portfolios of projects that will be resilient to climate change.[232]

System-scale research on options for cascade management could reveal alternative operating rules that will be robust to climate change and provide greater benefits. Lee, et al., (2011) studied how to optimize flood control and hydropower within the Colombia River dam system given likely alterations to basin hydrology due to climate change. They found that optimized flood control release curves, compared to fixed status quo curves, could allow maintenance of flood management while increasing hydropower and also increasing availability of water for releases to promote fish habitat in the late summer.[233]

By incorporating climate change into how it identifies well-balanced development or management options, HbD can help both governments and the private sector manage climate-related risks and improve the resiliency of infrastructure systems and how they deliver benefits to society.

232 Wahid et al. 2016.
233 Lee et al, 2010.

Appendix E: Methods

1. **Global spatial analysis**
2. **Estimating economic value of water-management services in HIB**
3. **Connectivity case studies**
4. **Tradeoff analysis**
5. **Magdalena financial analysis and case study methods**
6. **Sarawak case study methods**
7. **Reservoir and floodplain analysis**

1. Global spatial analysis

Hydrographic framework and analysis scale

In this study, we use a global hydrological framework based on HydroSHEDS to integrate all utilized datasets to a common scale. HydroSHEDS is a hydrographic mapping product created by World Wildlife Fund that provides river and watershed information for regional and global-scale applications in a consistent format.[234]

HydroSHEDS provides both detailed river networks as well as hydrological delineation into subbasin units. This study used both types of data and scales to calculate indicators, and to aggregate indicators and other data to the hydrological basins, the final unit of analysis and interpretation. The global river network was extracted from a drainage direction grid at 500-meter pixel resolution by applying a minimum size threshold for their upstream watershed areas of 50 km^2, or if their long-term average natural discharge exceeded 100 liters per second. In addition to the river reach scale, we use HydroBASINS level 4 for all subsequent statistical aggregation in the analysis. At the HydroBASINS 4 level, larger basins, such as the Amazon, are subdivided, whereas other, smaller basins remain as a single hydrological unit. This type and level of subdivision creates equally sized analysis units at a scale relevant to the HbD approach.

Datasets and key indicators

Runoff, discharge and habitat volumes

Estimates of long-term (1971-2000) monthly discharge averages, as well as runoff values, were derived through a downscaling procedure from the 0.5º resolution runoff and discharge layers of the global integrated water model WaterGAP.[235]

Based on discharge estimates and simplistic hydraulic geometry laws,[236] a first-level approximation of the dimensions of channel width and depth has been derived for each river reach. These values are then used to calculate habitat volumes (i.e. in-stream habitat space) for each river reach.[237]

Dams and reservoirs

We used a combination of two databases to derive attributes related to dam characteristics and impacts and we grouped the dams in three sets – existing dams, under construction dams and planned dams:

Global Reservoir and Dam (GRanD) database

Coordinated by the Global Water System Project (GWSP) and based on a variety of sources, the locations of nearly 7,000 of the world's largest reservoirs and dams were georeferenced, and attribute data were compiled, including storage capacity and main purpose.[238] Corresponding reservoir outlets, i.e. dam locations are linked to the HydroSHEDS stream network via their coordinates. The data is available at http://www.gwsp.org/85.html.

GRanD includes storage volumes of each reservoir, but does not include estimates of installed hydropower production. As a coarse first-order estimate, we calculated installed capacity as a function of storage volume using a linear relation between storage and energy production.[239] However, while there is a strong correlation between storage and energy production, large estimation errors may remain for some types of dams, especially run-of-the-river dams. Interpretations of the final values should therefore be made with caution. Furthermore, some dams regulate natural lakes with very high storage capacities, which produced unrealistic estimates. We identified 21 of these outliers and replaced their estimated energy values with confirmed values from the literature. Four dams were removed from consideration because these were not aligned with established river networks.

Database by Zarfl et. al. (2015)

This database includes a set of under construction and planned hydropower projects, their location, as well as projected installed capacity. To derive storage capacity not present in the original Zarfl database, but needed for calculating the 'Degree of Regulation', we used values based on a linear relationship between storage and energy production (see above paragraph for discussion of limitations).[240] A total of 166 Zarfl dams were removed as they were not aligned with established river networks.

Irrigation

The irrigation data were derived from the Global Map of Irrigation Areas [241]. For this analysis, we used the area irrigated by surface water which was presented as a percentage of the total area equipped for irrigation per pixel. Summary statistics were run on these two grids to determine the total area equipped for irrigation and the area irrigated by surface water per basin.

Urban population at risk from flooding

A population count grid was provided by LandScan,[242] and a MODIS grid [243] was used to delineate whether populations were rural or urban. The LandScan population count grid was combined with the MODIS urban extent grid to produce an urban population count grid.

Extreme flooding was derived from GIEMS-D15.[244] The extreme flooding extent is represented by the combination of the mean annual minimum, the mean annual maximum and the long-term maximum inundation grid. Next, the extreme flooding grid was combined with the urban population grid to calculate the number of urban inhabitants within the extreme flooding zone.

Fish Harvest

We derived an annual estimate for freshwater fish harvest from the world's rivers in the HydroBASINS using data from a gridded global map of riverine fisheries [245]. The fish catch is modeled based on river discharge using a 6-minute hydrography [246] dataset and constrained using national statistics[247]. The total annual fish catch was summarized for each hydropower-influenced basin (HIB) (see HIB methodology below). The summarized fish catch values were then normalized by basin area and classified by quintiles in figure 3.1 of the main body of the report. The annual estimate of fish harvest was also converted to the equivalent number of people whose animal protein consumption is from freshwater capture using country level data from the Food and Agriculture Organization of the United Nations (FAO 2014). The estimate for number of people is conservative because FAO lacks consumption data for many nations and/or values are known to be underestimates.

Freshwater Fish Species

Spatial data from IUCN's Red List of Threatened Species[248] was used to estimate the number of freshwater fish species in the HydroBASINs. IUCN's spatial database for freshwater fish is not globally comprehensive. Thus, we constrained the analysis to regions comprehensively assessed by IUCN, which include continental Africa, Europe, eastern Mediterranean and Arabia, India, eastern Himalayas and Indo-Burma, New Zealand and South Pacific Islands and the United States. Our analysis indicates that 4,221 fish species occur in hydropower-influenced basins that fall in regions compressively assessed by IUCN. Since our HIB also includes the entire Amazon Basin with an estimated 2,500 fish species and the entire Yangtze river basin with an estimated 426 species, we conservatively estimate that at least 7,150 fish species occur in the HIB[249]. Given that freshwater fishes comprise nearly 12,740 recorded species,[250] we conclude that at least 50 percent of global fish species occur in the HIB. Since fish species are not globally comprehensive in the IUCN spatial database, figure 3.2 in the report displays the HIB over Freshwater Ecoregions of the World shaded by their species richness.[251]

234 Lehner, et al., 2008.
235 (Alcamo et al., 2003; Döll et al., 2003; v2.2 as of 2014)
236 sensu Allen, et al., 1994
237 Lehner and Grill, 2013.
238 Lehner, et al., 2011.
239 Grill, et al., 2015.

240 Grill, et al., 2015.
241 GMIA; Siebert et al., 2013
242 Rose and Bright, 2014.
243 Schneider, et al., 2009.
244 Fluet-Chouinard, et al., 2015.
245 McIntyre, et al., 2016.
246 Wisser, et al., 2010.
247 See McIntyre, et al., (2016) for more details.
248 IUCN, 2017.
249 Junk, et al., 2007 (Amazon); Xing, et al., 2015 (Yangtze)
250 Levêque, et al., 2008.
251 Abell, et al., 2008.

Identifying basins impacted by hydropower (HIB)

Overview

We derived a global set of 'hydropower-influenced basins' (HIB) from a select group of the level 4 HydroBASINS where hydropower either does, or will, exert a major influence on rivers within the basin. In total, 441 (33 percent) of the 1,342 level 4 HydroBASINS are included in the HIB.

The HIB basins were selected using a filtering process that evaluates the Degree of Regulation (DOR), Degree of Fragmentation (DOF) and installed generating capacity of planned, under construction and existing dams in each HydroBASIN. The first filter selected basins that have a DOR greater than or equal to 10 or a DOF greater than or equal to 20.[252] We identified 420 basins with the first filter. The second filter added an additional 27 basins that were excluded under the first filter but which have 1,000 MW or more of system-wide installed capacity and either have a DOR greater than or equal to 5 and a DOF greater than or equal to 10. Finally, four additional basins were manually selected for the HIB based on contextual knowledge of the degree of hydropower development in the basins—one basin in Italy, two in France and one in Japan.

Calculating reach level indicators for HIB

Using the global river reaches in a river routing model called HydroROUT, which features an advanced implementation of connectivity and a novel implementation of object-oriented vector data structures in a graph-theoretical framework, we calculated reach level indicators, including Degree of Fragmentation (DOF) and Degree of Regulation (DOR).[253]

Degree of Fragmentation

River fragmentation indices measure the degree to which river networks are fragmented by infrastructure such as hydropower and irrigation dams. The Degree of Fragmentation (DOF) is a new fragmentation index at the river reach scale and is intended to primarily assess the level and extent of disturbance due to reduced longitudinal connectivity in the river system. It identifies river reaches up- and downstream of a dam as being fragmented, and it assigns levels of fragmentation based on distance from the disturbance as well as affected river flow quantities. The natural fragmentation effect of waterfalls has also been taken into account by incorporating a global database of waterfalls.[254]

Degree of Regulation

The Degree of Regulation (DOR) provides an index to measure how strongly a dam or set of dams can affect the natural flow regime of the downstream river reaches.[255] The concept of the index is based on the relationship between the storage volume of a reservoir and the total annual river flow at the dam's location. It is expressed as the percentage of flow that can be withheld in the dam's reservoir. For example, a dam that has a large reservoir on a river with small annual discharge will generally have a larger regulatory effect on the natural flow regime than a small reservoir on a large river.

We capped the DOR at 100 percent, which limits all multi-year reservoirs to the same maximum DOR. We also set DOR values below 0.1 percent to 0 percent to avoid inclusion of rivers with minimal impacts (mostly major downstream rivers affected by small and faraway headwater dams).

Aggregation of indicators to the HydroBASIN-scale

To derive a single, aggregated impact value for each sub-basin, we calculated volume-weighted averages of DOF and DOR across each sub-basin. At the river reach scale, we multiplied the DOR and DOF values with the habitat volume of the respective river reach, and then summed the weighted values for each basin and finally divided the sum by the total habitat volume of all river reaches in the sub-basin.

Classifying the HIB into four categories

To provide a contextual framework for the different types of river basins in the HIB, each of the HIB basins was assigned a score to indicate its hydropower development maturity and a score to indicate its level of competition for water. These two axes were used to classify each basin in the HIB into one of four quadrants as depicted in Figure 2.3 of the body of this report and shown in the scatter plot (Figure E1) below.

252 Grill, et al., *in prep.*
253 Grill, et al., 2015.
254 Ariwi, et al., *in prep.*
255 Dynesius and Nilsson, 1994; Lehner, et al., 2011.

Level of hydropower development

Hydropower maturity was based on the degree to which a given basin's hydropower development was fully mature as opposed to having more hydropower development planned in the future. The maturity metric was calculated as an index where a value of one a denotes fully mature (a basin with existing hydropower dams and no future dams planned) and a value of zero denotes a basin with no existing hydropower dams but proposed hydropower dams for the future.

Four components were used to measure hydropower maturity. These four components include 1) the number of dams, 2) the generating capacity of dams in the basin (MW), 3) the Degree of Regulation (DOR) and 4) the Degree of Fragmentation (DOF). The maturity index for a basin can be simply summarized as:

$$MI = \frac{\left(\frac{C_c}{C_f} + \frac{}{DOR_f} + \frac{DOF_c}{DOF_f}\right)}{4}$$

Where MI = maturity index, Cc = Count of dams (current), Cf = Count of dams (future), MWc= Generating, capacity (MW) of dams (current), MWf = Generating capacity (MW) of dams (future), DORc= Degree of Regulation (current), DORf= Degree of Regulation (future), DOFc= Degree of Fragmentation (current), DOFf = Degree of Fragmentation (future)

Of note, DOR and DOF, which assess potential flow alteration and longitudinal river fragmentation, respectively, can be influenced by dams outside of a given basin. For example, a basin that does not have a hydropower dam but is located downstream of a basin that has a large dam could receive a DOR greater than zero. Thus, it is possible for basins with no current or future dams to have a basin maturity score greater than zero.

Basins with no future dams or future impacts from DOF and DOR were manually assigned a maturity score of zero (division by zero is undefined). Finally, basins with a maturity index greater than or equal to 0.5 were classified as basins with current development while basins with a maturity index less than 0.5 were classified as future development.

Level of competition for water

A water abundance metric was calculated for each level 4 HydroBASin using a water depletion data that incorporates seasonal and dry-year water scarcity.[256] This water depletion data, which is provided as raster data at five-minute cell resolution, is based on the fraction of available renewable water consumptively used for human activities within 15,091 WaterGAP basins that cover 90 percent of the earth's land surface. Several categories of Baruman et al's data were combined to create a single water depletion category, including annual depletion equal or greater to 75 percent and dry year and seasonal depletion.

The water abundance index was calculated as the percent of each HydroBASIN area that was classified as depleted. Note that the basins used in the WaterGAP analysis are not identical to the level 4 HydroBASINS. Thus, the metric calculated herein is a summary analog of Brauman's water depletion metric, but it does not measure depletion directly. The following equation was used to calculate the water abundance index:

$$W\,AI = \frac{Area_D}{Area_T}$$

Where WAI = Water Abundance Index, AreaD = Area of the basin (km2) that is water >=75% water depleted on an annual basis or dry year or seasonally water depleted, AreaT = Total area of the basin (km2)

From this water abundance index, a threshold value of 0.1 was selected to classify basins as water abundant or water scarce. This threshold was selected based on a review of the data and assessment of the case study basins in the context of the WAI.

2. Estimating economic value of water-management services in HIB

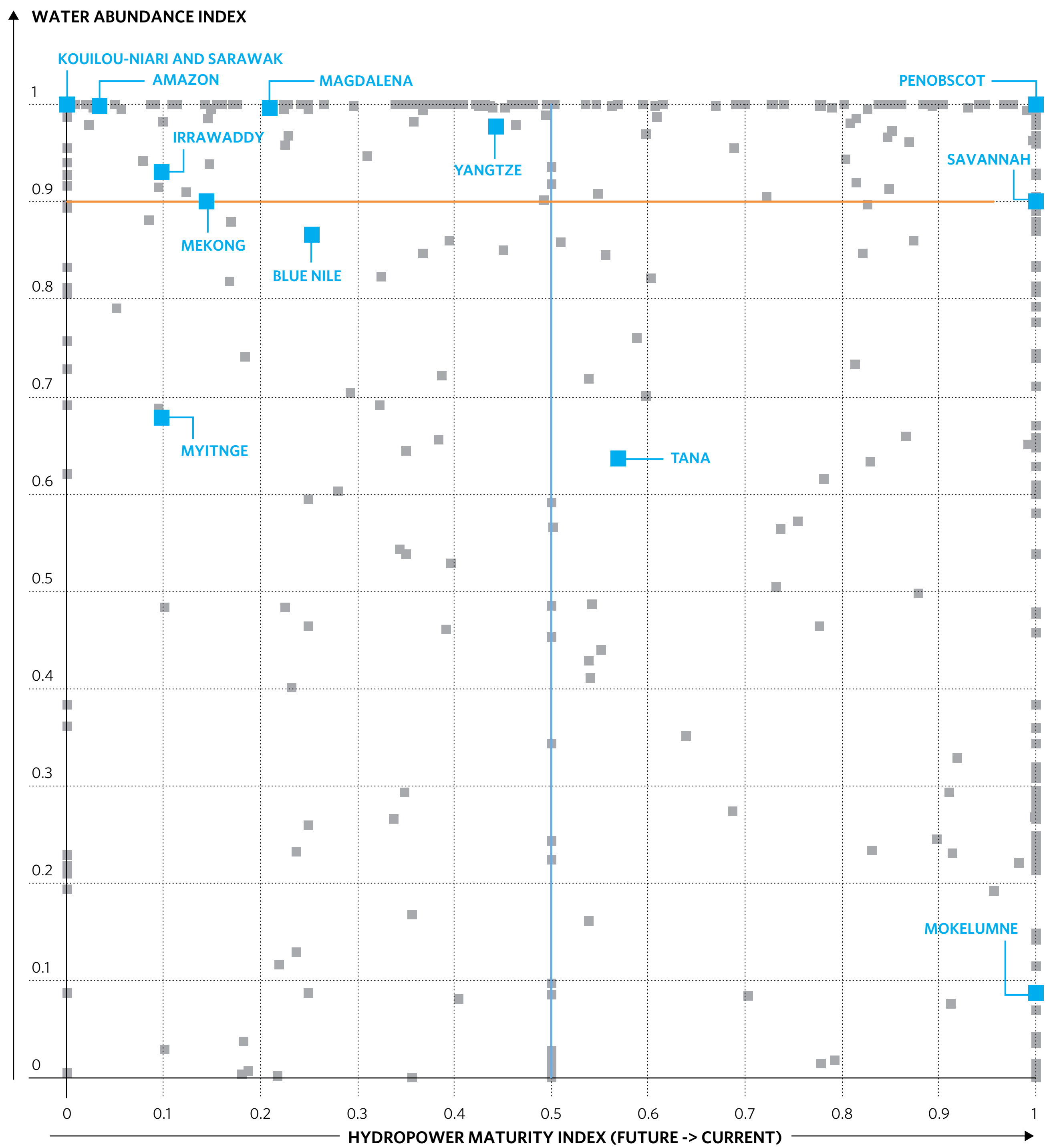
Irrigation

To estimate the value of water for irrigation from reservoirs in the HIB, we took the irrigated area from the global analysis describe above and multiplied it by an estimate of the per hectare additional value for agricultural land provided by irrigation. To get a rough approximation of the value of irrigated land we focused on rice, as 61 percent of irrigated area is for cereals, 47 percent of irrigated cereals area is for rice for a total of approximately 75 million hectares of irrigated rice, about half the total area planted in rice globally.[257] The value of irrigated land varies dramatically based on the crop, but because of the prevalence of rice we are using it as a broad proxy.

256 Brauman, et al., 2016.
257 Ricepedia, "Rice Productivity."

FIGURE E1.

Scatter plot showing HydroBASINS and case study basins categorized by the two axes – level of development and level of competition for water



The global production of rice is approximately 700 million tons, which translates to an average production of 4.4 tons/ha/year, through that mix of rainfed and irrigated land. For crops in general, irrigation can double productivity (though of course that can be much greater in desert regions). Based on the average productivity and the proportion of rainfed to irrigated land, we estimate a productivity of 3 tons/ha for rainfed and 6 tons/ha for irrigated. The productivity difference attributed to irrigation can be used as an estimate of the economic value of irrigation. At a current price of $380/ton, and a 3 tons/ha advantage for irrigation translates to a value of $1140/ha or irrigated land. [258] As a rough estimate of the range of potential values from irrigation, across crops and regions, we took 50% and 200% of that value. Multiplied by the 178 million ha of irrigated land in HIB, that's an annual value between $102 billion and $ 408 billion per year

Flood management

To estimate the potential value of flood management from reservoirs we estimated flood damages that occur within the HIBs. In 2016, river floods were responsible for $56 billion, representing one-third of all economic damages from natural catastrophes.[259] We used that as an upper end of the range and took half the value as the lower end of the range. Using the results from the analysis of the extent of population at risk from flooding, we found that 70% of risk was found within the HIB. Seventy percent times the range of $28 billion – $56 billion yielded an estimate of flood risk in the HIB of $20 billion to $40 billion.

Water supply

To estimate the value of water supply in HIB we first estimated the total reservoir storage volume dedicated to water supply in the HIB and then multiplied that by an estimated economic value for a unit volume of water for municipal supply.

For multipurpose reservoirs, GRanD assigns total reservoir storage to each named purpose. For example, a reservoir with with a storage volume of 500 million cubic meters (MCM) with purposes of hydropower, irrigation and water supply would assign 500 MCM to each purpose. This obviously overestimates water supply from these multipurpose reservoirs so, to be conservative, for any multipurpose reservoir within GRanD we assigned only 5% of the total storage to water supply. This resulted in a total of 41,000 MCM. We added that to 100% of the storage within single-purpose water supply reservoirs (47,000 MCM) to get a total of 88,000 MCM.

The economic value of municipal supply is difficult to estimate as it is clearly far higher than the price for which it is sold. Cities could not exist without a reliable water supply and, for many, there are few alternatives. A recent estimate from the United States Environmental Protection Agency reported that the value of municipal supply could range "up to $4500/acre foot"[260] At 811 acre foot per 1 MCM, this equates to $3,649,500 per MCM. We took that as the upper range, and half of that as the lower range, leading to an estimated value for water supply in the HIB between $161 billion and $321 billion.

3. Connectivity case studies

Many species of migratory fish require access to inland waters at some stage of their life cycle. Dams are often complete barriers to the free movement of migratory fish resulting in substantial population reductions. Even dams with fish passage facilities can drastically hinder the passage of fish. Further, the placement of dams in a basin can have a significant impact on the amount of habitat that is accessible from the river mouth for a migratory fish. A single large mainstem dam close to the river mouth might have the same generating capacity as two smaller dams higher in the basin, but would have a much more significant impact on migratory fish by limiting access to the entirety of the basin above it.

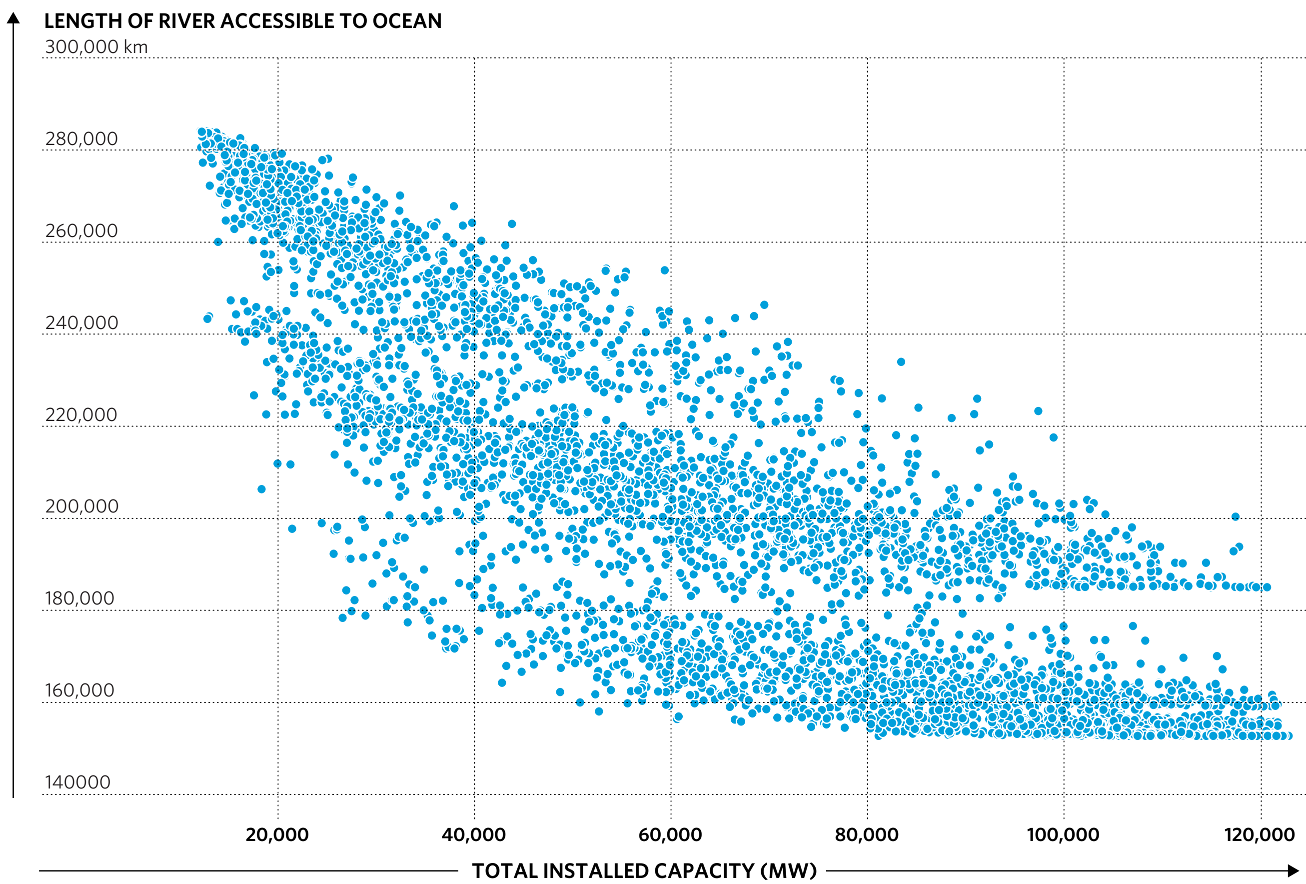
A connectivity assessment was conducted on a subset of the case study basins including the Amazon, Irrawaddy and Mekong, to evaluate how different configurations of future dams could be selected to generate similar hydropower with dramatically different impacts on the amount of accessible migratory fish habitat. We quantified the extent of connected channel network as a proxy of the habitat for migratory fish that make long distance migrations.

The scatterplot in Figure E2 depicts the kilometers of river in the Amazon basin that have unrestricted access to the ocean under different scenarios. Each point on the scatter plot represents a scenario, or a portfolio of dams, that includes all the existing and under construction dams in the basin in addition to a random set of proposed dams from the database. A separate database of existing, under construction and planned dams was used from CGIAR's Research Program on Water, Land

258 Index mundi, "Rice Monthly Price." March 1987 – March 2017.
259 Munich RE, 2017.
260 EPA 2013; page 13

FIGURE E2.

Scatter plot of dam scenarios in Amazon case study where each point is a portfolio of potential dam projects. The plot illustrates the variability of potential impacts to migratory fish habitat (>= 10 cms) for a given generating capacity.



and Ecosystems for the Mekong case study analysis.[261] Five thousand random scenarios were run using HydroROUT[262] to generate Figure 2. For each scenario, the combined generating capacity, in megawatts, of the dams was summed and plotted against the length of river, in kilometers, that remained accessible from the ocean assuming each dam was a complete barrier to migratory fish movement. To prevent an overestimation of river habitat that would likely be used by migratory fish, a 10 m3/s mean annual flow threshold was applied to the river dataset. This amount of river discharge, which roughly corresponds to fourth order rivers in the Amazon, is a conservative estimate of rivers that are likely used by migratory fish where streams as small as third order are commonly used by migratory fish (P. Petry, personal communication, February 22, 2017).

Across virtually the entire range of generating capacities, there are portfolio options which have far fewer impacts on access to migratory fish habitat than other portfolios with the same generating capacity. For example, portfolios of dams in the Amazon basin (figure 1) which generate 60,000 MW include portfolios which leave over 250,000 km of river accessible to the ocean as well as portfolios which leave less than 160,000 kilometers – a reduction of 90,000 km for the same amount of electricity.

4. Trade-off analysis to support Hydropower by Design

Trade-off analysis of hydropower development and management involves understanding how operation of existing dams and siting, design and operation of new dams could impact the achievement and distribution of water and energy benefits amongst sectors and regions, and using this understanding to better design hydropower systems. It is both an analytical approach to system optimization (its management and/or planning) and a process whereby different stakeholders deliberate and refine designs to arrive at desirable outcomes. Its aim is to enable strategic development and management of hydropower resources such that outcomes are efficient, robust, sustainable and acceptable to a range of stakeholders groups.

The approach begins with using a river basin simulation model, the foundational tool of integrated water resources management, to represent the core processes of the river system.[263] This can include river flows, storage in dams and lakes, reservoir release rules, and water allocation between sectors (if relevant), amongst other variables. Infrastructure operating rules are represented in whichever way they are most relevant for a particular system (e.g. reservoir storage-release tables, etc). In addition to such variables, a series of performance metrics can be tracked to record the impact of water flow, storage or use; examples include hydropower production, irrigation water yields, ecological benefits etc. Typically, these metrics are designed iteratively with stakeholder involvement to ensure the most important features of the water system are being considered when evaluating future interventions or management changes.

To quantify how differences in dam management options impact performance of the system, the simulation model must be able to represent different operating rules for dams. In the case-studies of this report dam releases are controlled by a storage-dependent release rule curve which dictates how much water should be released at each time step as a function of water stored behind the dam (see an example in Figure E3).

This water management simulation model is then linked to a multi-objective search algorithm which efficiently filters through the available portfolios of development options (with each option defined as a combination of dam sites, dam sizes, and their operating rules, etc.), which can number in the billions, to find those options that perform best. Specifically, it seeks investment options that maximize (or minimize) each of the metrics until no further improvements can be found in one dimension of performance without simultaneously decreasing one or more other metrics. This process identifies the "efficient" (Pareto-optimal or "non-dominated") set of hydropower investment and/or management options (black points in Figure E4), which can be displayed in trade-off plots: "trade-off curves" (in two dimensions) or trade-off surfaces (in multiple dimensions), which allow decision-makers to better visualize their options and balance performance across many factors.

This optimized set of investment options will map out a trade-off curve made up of the most efficient ('Pareto-optimal') combinations of assets and management rules. This output helps system planners and decision-makers select assets which perform well together, achieving an appropriate mix of the different water-related benefits. Results, even in complex systems with many development options and many relevant metrics of system performance, can be interactively explored using online tools. How trade-off analyses can be integrated within a Hydropower by Design process, including data needs and stakeholder engagement, is discussed in Appendix A.

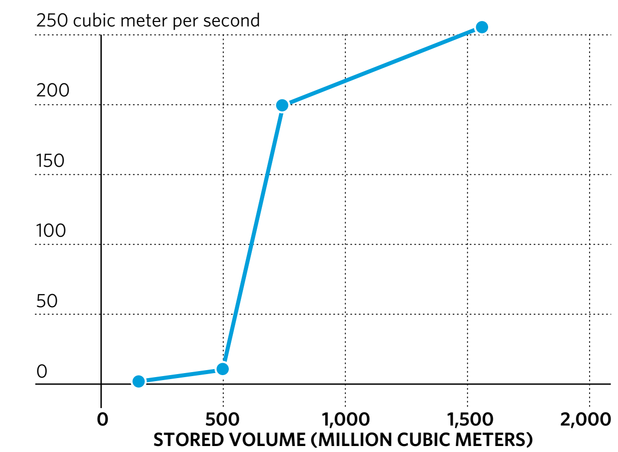


FIGURE E3.

An example of a storage-dependent release rule curves for a simulated dam. Each point helps define a reservoir's release rule and can be included in the search process.

261 WLE, 2017.
262 Grill, et al., 2015.
263 Matrosov, et al., 2011.

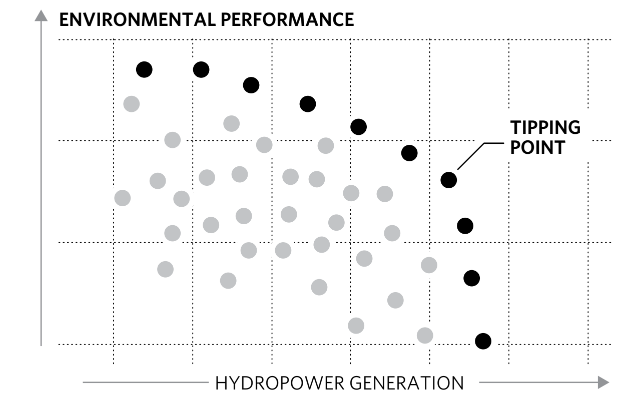


FIGURE E4.

Tradeoff plot showing how each portfolio of different hydropower investments and/or management options (each point) produces a different combination of environmental and hydropower benefits. The black points denote the non-dominated, highest performing portfolios (Pareto-efficient), the grey points are the dominated portfolios. The dark points trace a curve that will be of interest to system planners and decision-makers. Note the inflection or tipping point in this plot, beyond which more hydropower production comes with a greater relative decline in environmental performance.

Examples of applications of a tradeoff approach are increasing, and it has shown to be effective for complex and intertwined engineered and natural systems with varied stakeholders. In the United States and the United Kingdom the approach has been used by several water utilities; see Basdekas (2014) for US examples, and Matrosov, et al., 2013 and Huskova, et al., 2016 for applications to planning UK water utility investments. In the developing world context other recent examples exist, including Hurford and Harou (2014) for hydropower and river basin planning in Kenya and Geressu and Harou (2015) for hydropower dam planning in East Africa. Recently this approach was used in projects funded by the World Bank (WB, 2016) and by DFID (TNC, 2016).

5. Magdalena case study analysis

The flow chart below (Figure E5) and associated explanations describe how PSR processed three different scenarios: (1) Business as Usual, (2) Engineering Optimization, and (3) Social and Environmental Risk Optimization. The 'Narratives' scenarios were also processed per the (3) methodology, however based on a smaller number of pre-defined candidate sites as narrowed down by TNC staff.

After each PSR scenario analysis, TNC staff post-processed the respective portfolio of hydropower sites to calculate cumulative social and environmental impacts. This analysis drew upon information collected over the course of TNC's several years of engagement in the basin, and was processed using the MATLAB software program. Data layers that were incorporated for impacts analysis include:

1. **Environmental:** Hectares impacted of páramos, dry forest, wetlands, national park reserve areas, regional natural park areas, national forest reserves, regional forest reserves and second law reserves. Cumulative impacts across the portfolio were also captured by calculating cumulative free-flowing river length, degree of river regulation, and sediment transport alteration.
2. **Social:** Hectares impacted for indigenous communities and post-conflict areas.
3. **Economic:** Hectares impacted of productive lands including agricultural zones, grasslands and areas with mining titles.
4. **Demographic:** Number of population displacement.

We present a sub-selection of these raw data impacts under the 'Cumulative Outcomes' scenario analysis sections.

For each scenario, we also calculated a social impacts index and an environmental impacts index. These indices provide a cumulative look across the variables listed above, with the environmental index referencing the aforementioned environmental data layers, and the social index referencing the social, economic and demographic layers as listed above. These indices are presented on a normalized basis, with the maximum disturbance for each impact variable across the scenario representing a benchmark against which the other scenarios would be benchmarked on a relative basis.

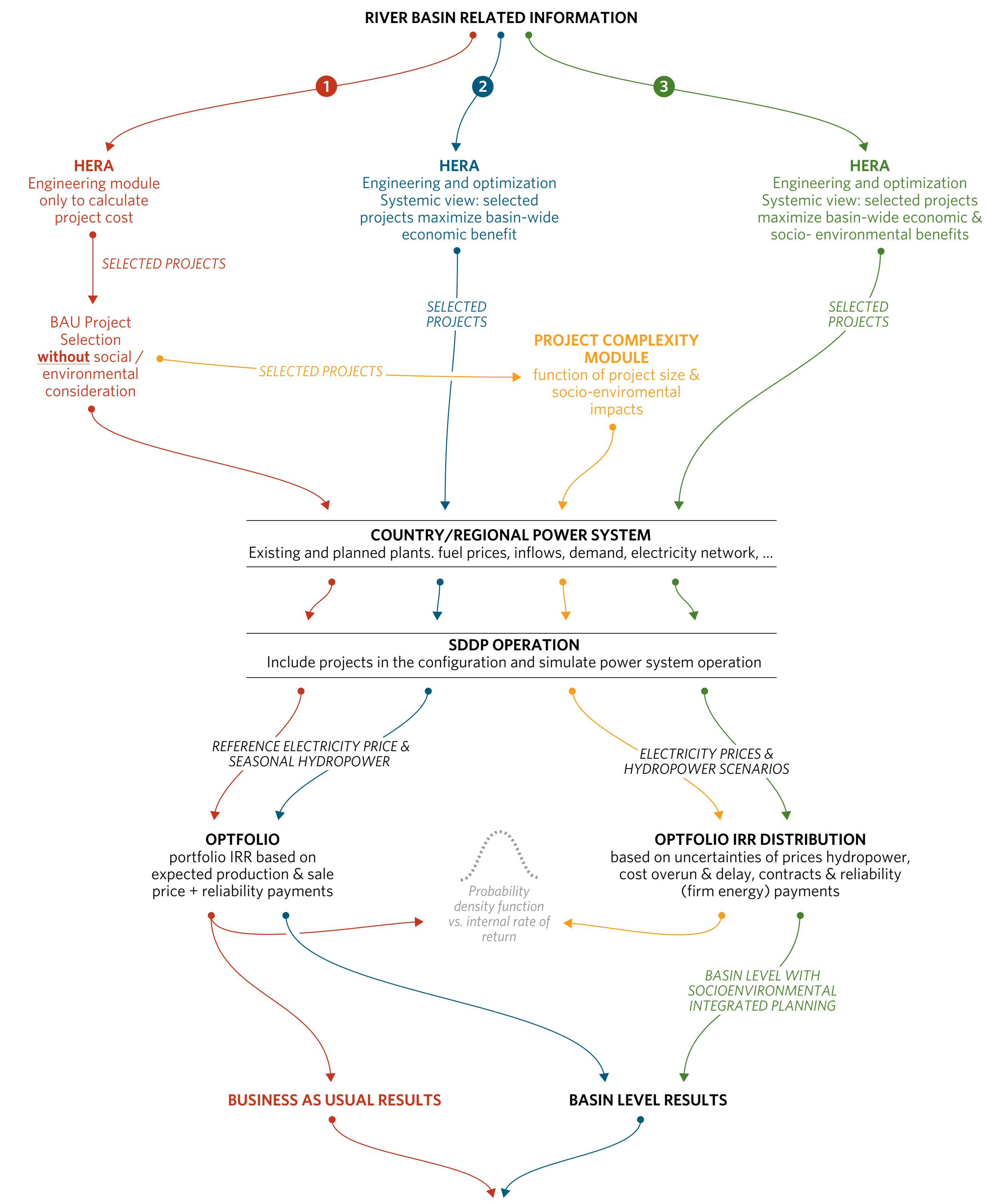
6. Sarawak case study methods

Method: Using Grid Simulation to Compare Cost and Benefit of Viable Energy Mixes

We compare the generation and environmental costs of different energy technologies through modeling the capacity expansion necessary to meet Sarawak's demand in 2030 under four different energy demand growth assumptions: continued Business as Usual (BaU), an aggressive 7% p.a. growth, 10% p.a. growth and the SCORE expectation. To do this we use PLEXOS, a commercial capacity expansion model built on a mixed integer linear program and collect (i) publicly available data on fossil fuel, hydro, solar and wind resources and biomass waste availability; (ii) data on build, operation and maintenance costs; (iii) local

FIGURE E5.

Flow chart of steps in the analysis of various hydropower development scenarios for the Magdalena.



FLOWCHART STEP	DESCRIPTION
River Basin Related Information	A hydrological model of the Magdalena and set of candidate sites was constructed using the following data sets: • Hydrological Regime determined from network of gauge stations • Digital Terrain Model was generated from NASA's SRTM database • Candidate sites were used from the 1979 master plan created by the Colombian government with support from the German Cooperation Agency. This study generated nearly 100 sites on the Magdalena's main stem as well as several of its tributaries • Geological Map used to determine certain construction costs • Population Density, Transportation Network, and Vegetation Coverage Maps used to determine certain negative externality costs
Country/regional power system Existing and planned plants, fuel prices, inflows, demand, electricity network...	• Construct generalized power system model that incorporates (1) plants already in existence / under construction, (2) types and prices of fuels for thermal energy, (3) capacity of transmission networks, and (4) projected regional demand varying across time.
HERA Engineering module for project reference cost	• Generate candidate site engineering layouts by testing different dam design across major engineering arrangements. These include dam types (earth, rock-filled, concrete, rolled concrete), water dissipation structures (stilling basin, ski jump), turbine types (Bulb, Kaplan and Francis, depending on water head), river diversion schemes (tunnel, channel). Different layouts from these engineering options are tested by combining structures and exchanging their relative positions (e.g. water intake on the right, spillway on the left), an iteration process that continues until a good match between the terrain and project layout is identified. • Calculate estimated engineering budgets by integrating design layouts and cost components (e.g. civil works such as volume of concrete/steel/earth excavation required, electromechanical equipment acquisition, land acquisition, etc.). • Select lowest-cost design alternative. This process can be repeated across all candidate sites and potential water heads, generating several thousand alternatives to consider.
SDDP Operation Include projects in the configuration and simulate power system operation	• Run SDDP production cost model that integrates the defined set of hydro plants into other forms of energy generation (intermittent renewables, nuclear, thermal). This model also integrates seasonal demand, as well as transmission networks. SDDP optimizes the supply of demand while considering reliability requirements (eg. reserves), technology-dependent constraints (minimum and maximum generation, ramping constraints, environmental flows for hydro plants, etc.), resource uncertainty (river flows, wind velocity, etc.) and transmission constraints (flow limits, losses, etc.). Time steps can range from monthly to hourly. SDDP output results of interest for this study are hydro generation and market prices per hydrological scenario.
BAU Project Selection without social/ environmental consideration	• Conduct BaU Project Selection by utilizing a 'cherry picking' methodology that prioritizes sites on an incremental, individual basis according to highest Net Present Value. After each site selection, the basin is reset according to the new topography and hydrological profile. Profit is calculated via HERA model to be the sum of electricity price multiplied by the amount of energy generation, minus plant construction and maintenance costs.
Project complexity module function of project size & socio-environmental impacts	• Incorporate environmental and social risks by testing different dam designs (e.g. powerhouse configurations, impoundment types, spillway orientations, turbine types, river deviation schemes) against cost inputs, terrain features and hydrological profile. Repeat process across all candidate sites and potential water heads, creating several thousand alternatives to consider.

FLOWCHART STEP	DESCRIPTION
HERA Engineering and optimization Systemic view: selected projects maximize basin-wide economic benefit	• HERA formulates the basin-wide hydropower portfolio selection process as a mathematical programming problem. Binary variables are assigned to each candidate project for selection. The objective function is to maximize the difference between portfolio electricity sales revenues and corresponding development costs. Constraints include reservoir min/max levels, water balance for dams in cascade, turbine outflow to power relationship, among others.
HERA Engineering and optimization Systemic view: selected projects maximize basin-wide economic & socio-environmental benefits	• A variant of the previous application of HERA with development risks being incorporated in the development cost of projects due to eventual entrance delays and cost overruns. Project risk premium depends on its social and environmental complexity and is fed into HERA for portfolio selection.
Optfolio "as planned" project IRR distribution based on energy sales in the market + contracts + firm energy payments	• Create investor return profile (ex- risk considerations) using PSR Optfolio software to create projected IRR distribution curve. This is based on market price of regional energy, contractual arrangements, reliability payments associated to firm energy, expected depreciation, debt amortization and interest payments and a four-year anticipated construction period. • CAPEX costs are distributed across a four-year construction period (35% / 30% / 20% / 15% respectively) • Fixed and Variable OPEX costs are assumed as 6% of project revenues
Optfolio "real life" project IRR distribution based on energy sales in the market + contracts + firm energy payments	• Create investor return profile (including social and environmental risk considerations) using same Optfolio methodology immediately above. • Project delays and cost overruns are applied to candidate projects based on a social and environment complexity index developed by TNC. Project-level social and environmental impacts were considered for each individual candidate site, with a resulting weighting of approximately 80% social (which included variables such as population displacement, economic areas affected, and post-conflict areas impacted) and 20% environmental (which includes layers such as losses of natural park areas, regional forests, wetlands, and páramos). Separately, we conducted a literature review of peer-reviewed publications that address average hydropower development cost overruns and time delays. We determined the data set detailed in Sovacool et al 2014 to provide the most representative and current sample, and from this data derived distribution curves for average hydropower project development time delay and cost overruns. We transformed these distribution curves, which reflect all sources of project development risk, by assuming a 30% contribution factor from environmental and social causes (i.e. we down-scaled the original curve by 70%). We thereafter sampled the Magdalena candidate projects against this transformed curve on the basis of the candidate's complexity index to provide estimates of time delay and cost overruns due to social and environmental risk factors.

emission factors from generation technologies and (iv) data on local policy such as Feed in Tariffs (FiT).

We use PLEXOS first to map available primary energy resources, existing generation and potential generation options and then to analyze optimal system configuration under various constraints and assumptions of demand growth and implemented policy. PLEXOS is a commercial linear mixed integer power sector model developed and commercialized by Energy Exemplar It is used by academia, industry and planning agencies in many countries. We selected a commercial software package to make our modeling directly accessible to state planning agencies. We also use PLEXOS because of its flexible framework which is very adaptable to client needs and data constraints.

The SCORE plan revolves around a targeted nine-fold increase in energy output between 2010 and 2020, or from 5,921GWh to 54,947GWh, which represents a 16% growth rate. In terms of installed capacity this translates to an expansion from 1,300MW in 2010 to between 7,000MW and 8,500MW in 2020[264]. In our model we forecast demand to 2030 under four different assumptions in order to observe the effect of demand growth on optimal system configuration. We model both the SCORE growth assumption and a conservative historic growth assumption. We then model two intermediate growth rates – 7% per annum and a more ambitious 10% per annum. The scenarios (modeled for each growth rate) are:

The 'Reference' scenario, where we commit the generators that are currently on the SEB grid including the Bakun Dam. We do not commit (i.e. force) any other mega-dam projects;

1. The 'SCORE' scenario where the Bakun dam and the two dams currently under impoundment or construction (Murum and Baram) are built along with 7GW of other hydroelectric power;
2. The 'Feed-in-Tariff' scenario where the SEDA approved FiT rates in effect across Peninsular Malaysia and Sabah are applied to their respective renewable technologies in Sarawak;
3. The '20% 2020 RPS' where a 20% generation-based Renewable Portfolio Standard is implemented.

We also design policy scenarios to observe the effect of policy instruments relative to the mega-dam strategy. The policy scenarios modeled are:

1. The 'Reference' scenario, where we commit the generators that are currently on the SEB grid including the Bakun Dam. We do not commit (i.e. force) any other mega-dam projects;
2. The 'SCORE' scenario where the Bakun dam and the two dams currently under impoundment or construction (Murum and Baram) are built along with 7GW of other hydroelectric power;
3. The 'Feed-in-Tariff' scenario where the SEDA approved FiT rates in effect across Peninsular Malaysia and Sabah are applied to their respective renewable technologies in Sarawak;
4. The '20% 2020 RPS' where a 20% generation-based Renewable Portfolio Standard is implemented.

Much uncertainty exists over the cost of dam construction in Sarawak.[265] Sovacool and Bulan [26] estimate capital costs for all of the prospective dams, reporting US $4,643 million for Bakun based on direct interviews. This corresponds to US$ 1935/kW and corresponds with other cited ranges for Bakun.[266] A recent Oxford study by Ansar et al. [267] analyzes a sample of 245 large dams built between 1934 and 2007. The researchers find that three of every four dams suffer from cost overruns and for one of every two dams costs exceed benefits. The study finds actual costs are on average double their estimated costs and suggests a cost uplift of 99% to reduce risk of overrun to 20%. We apply this uplift to the Sovacool and Bulan cost estimates and obtain an average capital cost value of US $3870/kW, very similar to the NREL 2012 estimate for hydro power plant capital cost of US $3500/kW.[268] We apply this capital cost value to all major dams and use NREL values for all other cost estimates (Fixed O&M Cost, VO&M Cost). We also include the standard US $0.1/kWh water levy as a Variable O&M cost for dam operation.

264 Sarawak Energy Berhad, 2010.
265 Oh, et al., 2011.
266 Sovacool and Bulan, 2012.
267 Ansar, et al., 2014.
268 Black and Veatch, 2012.

For each generation technology modelled we take overnight build cost, variable cost and fixed O&M cost from NREL.[269] Hydropower cost estimates are previously described in Section 3.3.2. POME methane capture costs are taken from Chin et al.[270] as the technology is not included in NREL's study. We also consider the effect of the Malaysia Feed-in Tariff (FiT) program currently being rolled out in the state in accordance with Renewable Energy Act 2011 and Sustainable Energy Development Authority Act 2011.[271]

Generator-specific emission rates for conventional generation in Sarawak was obtained from CDM studies on Sarawak's commercial grid.[272] These studies report rates that are similar to average US generation emission rates from NREL reports.[273] We use the NREL emissions rates and heat rates for analysis purposes. For Palm Oil biomass technologies we take heat rates from SEB.[274] Emission rates for EFB biomass gasification plants are averaged across local CDM biomass project reports.[275] An emission rate for POME methane capture plants is taken from Harsono et al..[276] We choose US $10/ton CO2-eq as the emission or carbon cost and increase this cost to US $25/ton CO2-eq during sensitivity analysis. These carbon price points are taken from EIA outlook scenarios.[277]

We then incorporate the cost of direct forest land loss using land value estimates taken from the 2012 WWF Heart of Borneo (HoB) Study.[278] This study finds the estimated value of forest land (including primary and secondary forest, swamp forest and mangrove forest) to be US$900 per ha per year over the past decade and project a doubling by 2030. This is based on estimates of the weighted average potential profit from different land uses. By combining this with land intensity for generation types from literature (ha/kW)[279] we can apply an annual Forestland Value charge ($/kW per year) to our least cost optimization model to account for the direct loss of land.

In all scenarios other than the SCORE scenario, generators are committed according to the standard optimization function for least cost. See our paper,[280] published in Energy Strategy Reviews for details on resource availability data, sources for technology cost and performance parameters, method and a full description of results.

7. Reservoir and floodplains analysis methods

Estimating flood risk improvement for Middle Yangtze River Basin through integrating hydropower, ecosystem protection, and floor risk management.

The Nature Conservancy worked with China Three Gorges Project Corporation, between 2008 and 2010, to examine alternative operations of the then planned cascade of hydropower dams in the Jinsha Jiang, the principal main-stem tributary of the Upper Yangtze River. This investigation was initially focused on improving environmental flows downstream of the cascade into the National Native and Rare Fish Reserve. Because of the effect of flood control storage operations then planned for the cascade, the investigation was extended to look at alternative reservoir operations for hydropower, environmental flows and flood risk management.

Under contract with the Yangtze River Scientific Research Institute (a division of the Yangtze River Basin Commission) existing reservoir operating models for the cascade were utilized to test various operating scenarios. The scenarios ranged from the originally planned operation to a scenario maximizing hydropower production and environmental flows.

Under an additional contract through Nanjing University (Nanjing Institute of Geography and Limnology, and Chinese Academy of Sciences) and the Hydrological Bureau of Yangtze River Water Resources Commission, flood risk and magnitude of potential damages was assessed for the various scenarios. This was based on inundation maps developed from DEM data, rates and amounts of inundation from hydraulic models, and analysis of land use patterns and economic values.

The Chinese flood risk management plan for the Middle Yangtze River below Three Gorges Reservoir consists of utilizing flood detention areas to store excess flood water after Three Gorges flood control operations have been utilized to the maximum extent. This involves opening up diversion gates to route Yangtze River water into these off-channel areas, already designated and enclosed by a system of levees and dikes. The analysis done under these contracts was to quantify

269 Black and Veatch, 2012.
270 Chin, et al., 2013.
271 Chua, et al., 2011.
272 GreenTech Malaysia, 2011.
273 Black and Veatch
274 Sarawak Energy, "Palm Oil Biomass."
275 Kina Biopower, 2012.
276 Harsono, et al., 2014.
277 U.S. Energy Information Administration, 2013.
278 Van Paddenburg, et al., 2012.
279 McDonald, et al., 2009.
280 Shirley and Kammen, 2015.

the damages that occur in using these FDA's (including the costs of evacuation and refuge of FDA occupants during flood detention operations), and costs of capital construction and maintenance necessary for operation.

The flood risk study focused on two areas, the Middle Yangtze River area downstream of Three Gorges and Gezhouba Dams (referred to here as the "Middle Yangtze Segment"); and the Upper Yangtze between the cities of Yibin and Chongqing (known as the "Chuanjiang" segment).

The Middle Yangtze Segment has been the subject of flood plans by the Yangtze River Water Resources Commission (CWRC), including published plans in 1954 and 1998 which served as the baseline of comparison in the study. The plan consists of utilizing flood detention areas (FDA's) to store excess flood water after Three Gorges flood control operations have been utilized to the maximum extent. This involves opening up diversion gates to route Yangtze River water into these off-channel areas, already designated and enclosed by a systems of levees and dikes. While some flood risk management benefits from this area may continue down river as far as the city of Wuhan, the plan is primarily directed toward protection of the agricultural and small to middle-sized towns in the historic Yangtze flood plain area. This also the primary area of protection of Three Gorges Reservoir flood operations.

Those plans assumed flood control storage in the planned Jinsha Jiang four-dam cascade, then sized at 14 billion cubic meters, would add some additional layer of protection. However, the study demonstrated that, in fact, flood control storage in the cascade did not significantly change the incremental flood risk in the Middle Yangtze, partly because of flood control operations of Three Gorges, and partly because of flood inflows from tributaries entering the system below Three Gorges.

The study recognized that the Chinese flood management plan depended upon a significant investment in up-grading and, in some cases, initial construction of additional FDA facilities. This included improving levees, raising structures, constructing safety areas, installing early warning systems, evacuation routes and refuge areas. Financial resources for this up-grading were expected from national budgets, but were not yet identified or committed by the time of the report. Based on information from flood planning agencies, the commencement of construction was expected within 15 years, and construction of facilities would be phased over the ensuing 15-year period.

The proposal of the Nature Conservancy was to accelerate construction and on-going maintenance of these facilities by using hydropower revenues from the Jinsha Jiang cascade, specifically the additional revenue that would be made possible by changes in storage and operation described in the Yangtze case study in Chapter 5. Here we describe how we estimate the improvement in flood-management performance, defined as the net present value of reduced flood losses an on annualized basis, between accelerated investment (with the HbD reoperation) and originally planned construction. Accelerated investment in facilities would be financed using committed future hydropower revenues from the cascade to raise capital through bonding.

Loss from an event requiring the use of flood detention areas was tabulated for each FDA, including the direct damage from inundation, and the loss from evacuation and sheltering people. These were expressed as billion Chinese RMB; at the time of the report the exchange rate to US$ was 6.8.

For the upper four FDA's, (Jingjiang, Yuanshi, Huxi and Renmindyayuan, which were most protected by operations of Three Gorges Reservoir) a probability of the occurrence of use of the FDA was determined by CWRC flood managers to be 1 in 100, or 1%. The loss from an event was multiplied by one percent to reach the annualized loss. For the lower two FDA's (Hong-Hu, and Jiangnanluch, which receives little or no risk reduction from Three Gorges operations), the probability of an occurrence was determined by CWRC flood managers to be 1 in 50, or 2%. The loss from an event was multiplied by two percent to reach the annualized loss (Table E1).

By reducing flood storage volumes in the upstream cascade and shifting greater emphasis to flood-risk management onto the downstream floodplain in the Middle Yangtze segment, the system could generate greater reservoir benefits (hydropower), up to 10%, and reduce flood risk across a wider range of flood levels and sources than could be provided by flood-control in the four-dam cascade.

The annualized losses avoided by the necessary improvement to the FDA system were accumulated for each of the two cases: 1) construction financed by the Sustainability Fund ("no flood control storage in the cascade") starting year one (in this report, the HbD option); and 2) construction financed by Chinese budgets, business as usual, starting after year 15, with the full amount of planned flood control storage in the cascade. The NPV of those two cases was compared at various time points.

TABLE E1.

Losses from flood events with either a 1:100 probability or 1:50 probability within Flood Detention Areas (FDAs) in the middle Yangtze floodplain and annualized losses. FDAs with 1:100 risk include Jinjiang, Yuanshi, Huxi and Renmindyayuan. FDAs with 1:50 risk include Honghu East and Jiangnanluch.

	FDAs w/ 1:100 risk	FDAs w/ 1:50 risk	Total
Loss from inundation,	3.36	2.00	5.36
loss from diversion and evacuation	4.70	0.33	5.03
Total Loss (billion RMB)	8.06	2.32	10.39
Annualized loss (billion RMB)	0.08	0.05	0.13
US$ @ 6.8 RMB/$	**12,000,000**	**7,000,000**	**19,000,000**

The results suggest that, through earlier investment in improvements, flood risk management could be improved dramatically over the next 15 years (NPV as high as 142% greater), and beyond continuing to a level of 18% improvement as far as 40 years out. The most representative comparison was selected at the 35 year point, representing fifteen years of accelerated flood risk reduction, followed by 20 years of business as usual. That comparison shows a 26% improvement.

Other benefits of the proposed reallocation of hydropower revenues from reducing or eliminating flood control storage were not quantified in this case study, but should be mentioned. Flood insurance paid for by hydropower revenues are likely a significant improvement. In theory, the Chinese government would be responsible for compensation following a flood event that required the use of the FDA's, but experience in many countries, as well as China, shows that compensation is not always funded in advance and maintained as expected. Flood insurance in a dedicated and continuously renewed plan should be seen as a major advantage.

Flood risk in the Upper Yangtze segment (known as the "Chuanjiang" segment, between the cities of Yibin and Chongqing), would have been abated to some degree by flood control storage in the cascade. Elimination of flood control storage under the proposal would have to have been compensated, and significant money was set aside for early investment in that segment. In fact, the same issue of budget and construction delay may suggest that early and certain investment there could also be seen as an improvement. Nevertheless, because of the need to offset flood risk control benefit arising as each unit of the cascade was constructed, no benefit was claimed in the case study analysis.

Finally, it should be noted that these benefits have been discussed solely in economic terms – the dollar value of accelerating the schedule of flood risk abatement facilities. In fact, in some of the FDA's, if construction were not completed right away, there would continue to be significant risk of loss of lives. There were over 1 million inhabitants living in the in HongHu FDA's at the time of the report. The planned levee to protect the portion planned for inundation (Honghu East FDA) had not yet been built or commenced. Subsequent inquiry shows that levee has still not been constructed.

The Savannah and Mokelumne case studies were conducted in a collaborative study with the US Army Corps of Engineers and the University of California, Davis. As noted in the case study, this was a proof-of-concept study and does not imply endorsement of reservoir management changes by the relevant dam operators. For methods on the Savannah and Mokelumne case studies, see The Nature Conservancy (2012), N. Burley (2011) and Burley et al. (2012).

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Hydropower by Design can identify strategic and sustainable hydropower systems that deliver economic value to countries, financial value to developers, and greater environmental values from rivers.

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The Nature Conservancy's water program is backed by 400 staff working across more than 500 freshwater conservation projects around the world. We use science, innovation and collaboration to meet the global challenges facing rivers today. By providing strategic guidance on hydropower planning, downstream flows and other solutions to protect and restore rivers, we have collaborated on conservation or restoration solutions with industry, governments and other stakeholders.

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WOCRD 1755