Water Working Notes

Note No. 22, November 2009

INTEGRATING ENVIRONMENTAL FLOWS INTO HYDROPOWER DAM PLANNING, DESIGN, AND OPERATIONS

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WATER PARTNERSHIP PROGRAM

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LIST OF ACRONYMS

CML	Institute of Environmental Sciences of Leiden University in the Netherlands
EIA	Environmental Impact Assessment
ELOHA	Ecological Limits of Hydrologic Alteration
ENEE	Empresa Nacional de Energía Eléctrica
FERC	Federal Energy Regulatory Commission
IHA	International Hydropower Association
NHI	Natural Heritage Institute
TNC	The Nature Conservancy
WCD	World Commission on Dams
WWF	World Wide Fund for Nature

FOREWORD

This Technical Guidance Note was primarily prepared as a contribution to the World Bank economic and sector work—mainstreaming environmental flow requirements into water resources investments and policy reforms jointly supported by the Environment Department and the Energy, Transport and Water Department. The technical note also forms a contribution to the Bank's hydropower investments. The main objective of the note is to serve as a guidance document as opposed to a technical manual. It has been developed to assist World Bank staff and their clients to identify ways to better incorporate the benefits associated with environmental flow protection into hydropower dam projects. Most of the material in this note will be equally applicable to hydropower dams with either multiple objectives or a single objective, but the integration of environmental flow protection into projects with multiple objectives presents some special challenges. In addition, many issues covered in this note will be applicable to other types of water infrastructure projects.

Technical expertise in water resources engineering, power engineering or freshwater ecology is not required to use the information contained in this note. It discusses some important environmental issues to be considered in hydropower dam projects and steps that can be taken to reduce the environmental footprint of dam projects. Annex 1 provides useful sources of related technical information.

The World Bank's Water Resources Sector Strategy points out that environmental impacts associated with many past dam projects have caused social and economic hardship for local communities. An increased awareness and application of tools and methodologies for assessing and reducing impacts to the environment can minimize undesirable consequences—such as diminished fisheries and loss of other ecosystem benefits valued by local communities—that might otherwise result from dam development and operation.

The World Bank Operational Manual on Safeguard Procedures includes guidelines relating to Environmental Assessment (OP/BP 4.01), Natural Habitats (OP/BP 4.04), and Dam Safety (OP/BP 4.37). The World Bank's *Making Sustainable Commitments: An Environment Strategy for the World Bank* outlines the importance of integrating principles of environmental sustainability in Bank-supported projects.

This note focuses on the management of river flow patterns to sustain river health. These water flow requirements are commonly referred to as "environmental flows." The World Bank has published a series of technical notes on environmental flows that provide a sound foundation for project teams involved in dam projects. These publications on environmental flow issues can be used effectively in conjunction with this technical note focused on integrating environmental flow considerations into hydropower dam projects. A publication produced by the World Bank's Latin America and Caribbean Region—*Good Dams and Bad Dams: Environmental Criteria for Site Selection of Hydroelectric Projects* (November 2003)—provides additional guidance for avoiding and mitigating environmental impacts of dams based on experiences in that region.

ACKNOWLEDGMENTS

The technical note was funded under the Environmental Flow window of the Bank-Netherlands Water Program Partnership. Its preparation was guided by Rafik Hirji (Task Team Leader) and Daryl Fields (co-Task Team Leader) and supported by Abel Mejia (Sector Manager, ETWWA).

This note was drafted by Brian Richter and Karin Krchnak of The Nature Conservancy (TNC) and Gregory Thomas of the Natural Heritage Institute (NHI), with support from Sarah Davidson and Jeffrey Opperman of TNC and Jessica Nagtalon of NHI. The authors wish to thank the following for their helpful reviews and input: Roberto Pereira d'Araujo, RCM Consulting and Project (Brazil); Fred Ayer, Low Impact Hydropower Institute; Rich Beilfuss, International Crane Foundation/Gorongosa National Park, Carr Foundation (Mozambique); Brian Bowen, Purdue University Energy Center; Dr. Cai Zhiguo, Three Gorges Project Corporation (China); John Gerstle, Hydrosphere Resource Consultants, Inc.; Chuck Howard, Cddhoward Consulting Ltd.; Helen Locher, Hydro Tasmania; Daene McKinney, University of Texas at Austin, Department of Civil, Architectural & Environmental Engineering, Center for Research in Water Resources; Jamie Pittock, World Wide Fund for Nature (WWF); Rose Mary Salgado, Empresa Nacional de Energía Eléctrica (Honduras); Thayer Scudder, California Institute of Technology; and Eric Weiss, BC Hydro.

This note was also reviewed by the following World Bank staff: Abel Mejia, Daryl Fields, Elena Correa, Barbara Miller, Alesandro Palmieri, Glenn Morgan, Vahid Alavian, and Rafik Hirji.

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EXECUTIVE SUMMARY

Hydropower dams provide society with substantial benefits, but, if poorly planned, designed or operated, they can also have serious consequences for the ecological health of rivers and the economic and social well being of communities dependent upon the goods and services provided by healthy rivers. Historically, assessments of the environmental and social effects of dams have focused primarily on areas in the immediate vicinity of a dam and its reservoir. However, dams can substantially modify river ecosystems for hundreds of kilometers downstream by changing the water flow (volume and timing), water chemistry, physical structure of river channels and floodplains, and hydrologic connections between upstream and downstream and between a river and its floodplain. These physical and chemical changes in a river environment lead to changes in biological conditions, including loss of plants and animals valued by local communities for food, building materials, and other cultural purposes.

Increasingly, water managers and dam planners are realizing the need to maintain adequate water flows and other habitat conditions to sustain river health and associated ecosystem services in river reaches located downstream of dams. This technical note focuses on one critically important element of this challenge: the need to maintain proper *environmental flows*. This term refers to a variable water flow regime that has been designed and implemented—such as through intentional releases of water from a dam into a downstream reach of a river—in an effort to support desired ecological conditions and ecosystem services.

When ecosystem services valued by local communities are fully considered and integrated along with all other management objectives, the prospects for optimizing both dam- and ecosystem-related objectives are greatly enhanced. Project teams can help avoid the loss of ecosystem services by considering environmental flow needs at the very earliest stages of hydropower dam development. This includes consideration at the *regional* scale, which includes national plans and can encompass many river basins and even multiple countries, and at the *local* scale, which is usually restricted to a single river basin or hydropower dam scheme. Societal objectives will be best met when regional development plans—which set broad regional, national, and/or river basin objectives for water and energy development and environmental protection—are paired with more detailed local-scale environmental assessments for individual dams or cascades of dams on specific rivers.

The specification and provision of environmental flows is key to sustainable hydropower development and water management. When environmental flow needs are assessed scientifically, water managers and hydropower dam planners and operators will understand the extent to which historical water flow patterns can be altered by hydropower operations without compromising a river's health and associated social benefits. In the past decade, environmental flow science has progressed considerably, and scientists now warn that maintaining *minimum low flows* is necessary but insufficient to maintain healthy river ecosystems. Instead, a naturally variable pattern of water flow is needed to sustain biodiversity and ecosystem services provided by rivers.

When carrying out regional or local environmental assessments, the best results are achieved through inclusion of all interested and affected parties from the very beginning. Active and early engagement of relevant water managers and dam planners, scientists, and other stakeholders in the planning process will help build a strong and influential constituency and foster a coordinated and consistent vision for the protection and management of a river. With proper input from stakeholders and attention to the needs and values of diverse interests, a tradeoff analysis can be undertaken to explore the optimal balancing of interests.

Choices and compromises among societal needs and values are involved in planning, designing and operating any hydropower dam or energy development program. The feasibility of integrating environmental flow needs into hydropower or multipurpose dam schemes has markedly improved recently due to improvements in dam design, technological advancements in electricity generation and transmission, and innovations in dam operations. To be most successful, these new approaches and capabilities need to be fully considered and integrated into both regional and local-level planning efforts. This technical note highlights a number of structural and operational considerations in hydropower dam development that can facilitate integration of environmental flow objectives, including:

- Variable outlet and turbine-generator capacities
- Multilevel, selective withdrawal outlet structures
- Re-regulation reservoirs
- Power grid interconnection
- Coordinated operations of cascades of dams
- Flood management in floodplains
- Sediment bypass structures and sediment sluice gates
- Fish passage structures

There is rapidly growing experience in integrating environmental flow releases and other environmental considerations into dam design and operations. The case studies included here offer valuable lessons—and cautions—that can inform future dam development.

The operating objectives for dam projects will likely change over time in response to changing social priorities, scientific and technological advancements, and climate change. This places a premium on maintaining flexibility to modify dam operations. Many recent experiences suggest that it is possible to improve the environmental performance of existing dams (called "reoperation") in a cost-effective manner, and sometimes with little or no social or economic disruption. Reoperation can be accomplished by implementing various water or energy management techniques that increase the flexibility of reservoir storage and releases such that environmental flows can be released into the downstream channel and floodplain. However, it will be far easier and more cost-effective to integrate environmental flow considerations into the planning and design of dams than to modify or retrofit the design and operation of existing schemes.

Even with the best-available expert knowledge and analysis, dam developers, governments, and stakeholders need to understand that the environmental consequences of hydropower dam development and operations cannot be predicted with complete certainty. To be ecologically and socially sustainable, water and energy development and management need to be perpetually informed by monitoring, carefully targeted data collection and research, and further analysis to address new uncertainties or surprises. Therefore, a program of monitoring, evaluation, and adjustment—commonly referred to as *adaptive management*—should be fully and explicitly integrated into any hydropower development or reoperation plan so that management approaches can be continually modified in response to increased understanding or changes in human or ecosystem conditions. The economic risks from uncertain future environmental constraints need to be addressed explicitly as part of an adaptive management strategy.

This technical note is intended to be a useful resource for World Bank staff and their clients involved in hydropower dam development projects. It describes tools and approaches aimed at protecting the ecological health of river ecosystems and the well being of human communities dependent on them, while meeting human needs for water and energy through improved hydropower dam development and operation.

I. INTRODUCTION

A primary challenge in water resource development is designing and operating infrastructure projects in order to provide social benefits while preventing the loss of natural ecosystem services due to dam development. The construction and operation of dams can cause myriad changes to river ecosystems, but many of these impacts can be avoided, minimized or mitigated through proper planning and management, thereby limiting disruption of ecosystem services and loss of biodiversity. It is now standard practice to evaluate environmental impacts in new dam proposals, but many of these environmental assessments are limited in scope to impacts in the immediate vicinity of a dam and its reservoir, especially during the construction process. However, evidence from dam development around the world suggests that more widespread and long-lasting ecological impacts can be expected *downstream* of dams.

Among the many environmental and social concerns involved in building or operating a dam, it is particularly important to maintain adequate environmental flow conditions downstream of dams. The term *environmental flow* refers to a variable water flow regime that has been designed and implemented—such as through intentional releases of water from a dam into a downstream reach of a river—in an effort to support desired ecological conditions and ecosystem services. Environmental flows are one tool in managing the impacts of hydropower dams, and thus each project should consider the range and appropriate combination of environmental management tools available. The purpose of this technical note is to offer a primer on ways to incorporate environmental flow considerations at scales ranging from individual rivers to entire regions.

The objectives of environmental flow protection vary widely, as evidenced by the Flow Restoration Database maintained by The Nature Conservancy (TNC), which includes more than 850 river flow management projects in more than 50 countries. In some instances, the purpose of environmental flow management is limited to restoring the population of a particular fish species; in other cases, a more holistic goal has been adopted, such as maintaining river health and ecosystem services.

A recent trend is to specify objectives for environmental flow management using a scaled measure of the desired health of the overall river ecosystem, sometimes referred to as *ecological management classes*. This approach, which appears to be gaining popularity, has some strong advantages. From a scientific perspective, an ecosystem management approach is preferable to a species-focused approach. From a social perspective, a choice among multiple levels of ecosystem protection provides flexibility in balancing dam-related benefits and ecosystem-related benefits. In applying this approach, different levels of ecosystem protection may be adopted across a large river basin or geographic region, reflecting the intent to manage different rivers for different purposes. It is important that stakeholders understand how various components of an ecosystem that are of interest to people—such as fish populations important to subsistence lifestyles or local economies—are likely to be affected by different levels of ecosystem protection, so that the tradeoffs involved in selecting for different ecological management classes are well-understood. It is also important to clearly define objectives for ecosystem service and biodiversity protection for each river being affected by, or protected from, dam development, as well as to consider how a suite of ecosystem-related objectives might be met through adoption of different objectives for different rivers in regional water development plans.

Most existing dams are single-purpose and small in size. The largest dams usually incorporate hydropower and serve multiple objectives, such as water supply, flood management, navigation, reservoir fisheries, and recreation. Other uses, particularly ecological values and ecosystems services, are much more difficult to measure in economic or consistent terms. Furthermore, there is comparatively little experience in applying economic techniques to the valuation of benefits from environmental flows. However, fully considering and integrating ecosystem-related objectives with all other management objectives increases the prospects for optimizing the full set of development benefits from hydropower infrastructure.

When flood management is required in dam operations, it usually will predominate over all other considerations. Electricity, which can be obtained from other sources, often is produced opportunistically in multiple-objective hydropower schemes, and can be greatly constrained by flood control operations. Flood management at a dam can also deprive downstream floodplains from much-needed inundation, often resulting in loss of important ecosystem services. However, significant opportunities may exist to increase hydropower production and maintain ecosystem services in downstream floodplains if the floodplain's natural storage capacity can be used or restored to its maximum potential. By allowing for higher flood releases from the dam—equivalent to small floods—that can safely inundate downstream floodplains, a lesser volume of flood storage is required in the reservoir, thereby creating an opportunity to use available storage for other purposes such as hydropower generation or water supply. Modifying downstream land uses or removing structures to allow temporary flooding during flood events may gain such flexibility in dam operations.

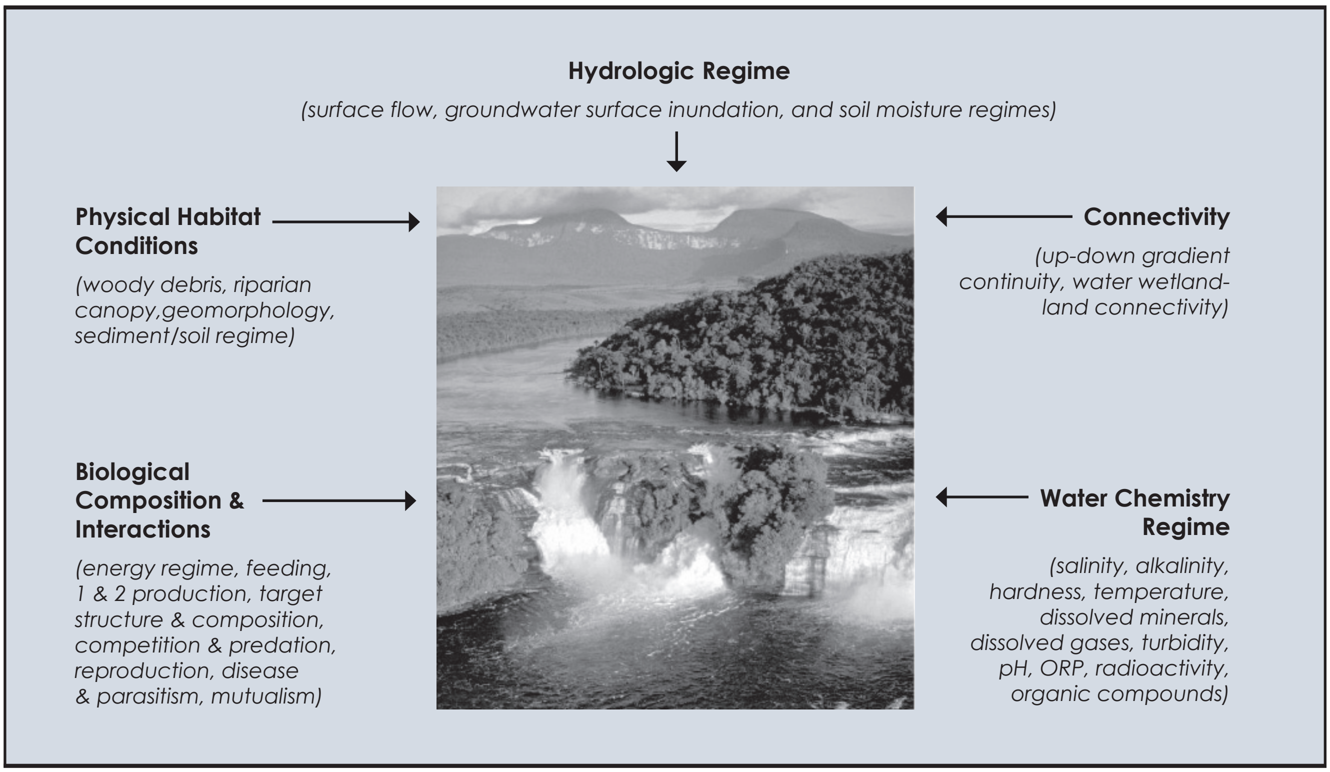
Four critically important points apply to both single-purpose and multiple-objective hydropower projects:

- Ecosystem-based objectives that address biodiversity and ecosystem service protection should be an integral aspect of planning efforts at all levels of governance and decision-making. When considering tradeoffs among alternative planning scenarios, the consequences for ecosystem-based benefits need to be explicitly articulated and considered.
- It will be far easier and more cost-effective to integrate environmental flow considerations into the planning and design of hydropower schemes than to modify or retrofit the design and operation of existing schemes.
- Environmental flow needs can and should be considered in every stage of a hydropower development project, including location (or *siting*) of dams, dam design, dam and reservoir operations, and reoperation (or changing existing operations).
- It is important to design hydropower schemes with built-in flexibility to accommodate changes in socioeconomic, and environmental demands, market conditions, changing technologies, and climate change.

II. KEY PROCESSES IN RIVER ECOSYSTEMS

Life in a river ecosystem is by nature highly dynamic. All aspects of the aquatic environment—water flow, physical structure of the channel and floodplain, chemical composition of the water, and water temperature—change over time frames that range from hours to years. Aquatic organisms have adapted to these variable habitat conditions. The reproduction and growth of many plants and animals actually requires different habitat conditions such as specific water flow levels at different times of the year, or during different stages of their life cycle. Therefore, when scientists describe the habitat conditions necessary to sustain a river ecosystem or a particular species, they commonly refer to these habitat requirements as a variable *regime* rather than a static habitat condition. Some of the most important environmental factors influencing river ecosystems are highlighted in Figure 1.

Figure 1. Major Environmental Influences on River Ecosystems



Source: Silk, N., and K. Ciruna, eds. 2004. *A Practitioner's Guide to Freshwater Biodiversity Conservation.* Arlington, VA: The Nature Conservancy. (Reprint edition published by Island Press in 2005.) Reprinted with permission. Photo Credit: Will Van Oberbeek.

Focus on the Flow Regime: A Master Variable

During recent decades, scientists have amassed considerable evidence that a river's flow regime—its variable pattern of high and low flows throughout the year, as well as variation across many years—exerts great influence on river ecosystems. Each component of a flow regime—ranging from low flows to floods—plays an important role in shaping a river ecosystem. Due to the strong influence of a flow regime on the other key environmental factors (water chemistry, physical habitat, biological composition, and interactions), river scientists refer to the flow regime as a *master variable*.

Scientists have been working closely with water planners and managers in river basins around the world to characterize the *environmental flow regime* needed to support ecosystem-related objectives. This note draws from the lessons learned from these experiences and outlines options for integrating environmental flow considerations into hydropower dam development.

Ecosystem Services Supported by Environmental Flows

Ecosystem services are defined as a variety of culturally and socially valued goods and services that human society derives from natural ecosystems. Freshwater ecosystems—rivers, lakes, streams, marshes, swamps, other wetlands, estuaries, aquifers, and deltas—provide a wealth of food and fiber, water purification, and fish and wildlife habitat, as well as opportunities for tourism, recreation, and cultural and spiritual renewal. They may also provide important transportation corridors. The full range of services provided by healthy freshwater ecosystems—which require adequate environmental flows—has only begun to be understood in the last several decades (Table 1).

Just as species evolve in response to variable environmental conditions, human cultures have evolved and adapted to the availability of resources and services provided by natural ecosystems. The availability of fish and other sources of food, reeds and timber for use as building materials, or the reliability of annual floods to supply moisture and nutrients that support floodplain agriculture or grazing have shaped and sustained human cultures around the world. People across the globe depend on fish as their primary source of protein, with some regions particularly reliant on fish due to the fundamental social and economic role of fisheries. Moreover, the genetic and chemical components of aquatic species may offer humans invaluable pharmaceutical and other benefits. Over many generations, the well being, livelihoods, and spiritual beliefs and cultural practices of local communities have become intimately tied to river ecosystems.

As with the scientific uncertainty associated with predicting ecosystem responses to flow alteration, the existence of considerable social uncertainty in adjusting to changes in availability of ecosystem services further argues for an informed, risk-based, and adaptive approach in hydropower development plans.

Impacts on Rivers and their Ecosystem Services

Human-induced changes to natural environmental conditions disrupt the ways that species interact with their environment and with each other. These changes, in turn, make it difficult (or impossible) for some species to persist in the ecosystem, or make it possible for invasive nonnative or problematic species to thrive, thereby potentially altering the ecosystem's biodiversity and functionality. These changes in ecosystem conditions can seriously affect the availability of goods and services that humans depend upon (Table 1).

Environmental assessments associated with hydropower dam projects will need to address the following question: How does the degree of habitat alteration associated with this project compare to ecosystem-related goals expressed by local communities and other stakeholders?

Because environmental flows are so essential to the health of river ecosystems and, by extension, the ecosystem goods and services upon which local communities depend, management of adequate flow conditions must be fully considered in planning, design, and operations. While some resources and services can be substituted or supplied by alternative means, such replacement or mitigation usually comes at significant cost to local cultures or society at large.

Managing Environmental Flows to Meet Social Objectives

When integrating environmental flow management into a hydropower dam scheme, it is important to understand that environmental flow releases from dams can be tailored to meet an array of social and economic objectives, and attain various levels of ecosystem protection. The integration of environmental flows should not be viewed as an all-or-nothing decision; instead, different aspects (or building blocks) of the flow regime, such as provision of occasional flood releases from dams to stimulate fish spawning, can be maintained or restored to varying degrees as necessary to accomplish ecosystem-based objectives. The type of environmental flow regime to be provided should be dictated by tradeoff analyses informed by an inclusive stakeholder decision-making process that fully considers the range of ecosystem benefits linked to environmental flows, as well as the social and economic costs and benefits of various options.

Key Points

- Species found in rivers, floodplains, and estuaries have become adapted to specific habitat conditions that facilitate completion of their life cycle. Necessary habitat conditions will differ among species, and even among different life stages of individual species. Therefore, an appropriate regime of variable ecosystem conditions such as water flow will be needed to support river species.
- The five most important factors influencing river ecosystem health include water flow (volume and timing), water chemistry, physical habitat, upstream—downstream and river—floodplain connectivity, and biological composition and interactions. Flow is considered a *master variable* because it exerts strong influence on the other four aspects and its management is central to attaining ecosystem-related goals. Dams can have a profound impact on all five of these aspects of river systems.
- Special attention needs to be paid to maintaining adequate water flow conditions (an environmental flow regime) to achieve ecosystem-related goals. Sustaining river, floodplain, and estuary species and ecosystem services requires much more than simply providing minimum low flows. A full spectrum of flow variability, ranging from low flows to floods, is necessary to meet ecosystem-related goals.
- The integration of environmental flow management into a hydropower dam scheme is not an all-or-nothing decision. Instead, environmental flow releases from dams—informed by tradeoff analysis—should be tailored to meet specific social and economic objectives.

Table 1. Comprehensive Checklist of Ecosystem Services Supported by Environmental Flows

Service category	Service provided	Key flow-related function	Key environmental flow component or indicator
Production	Water for people-subsistence/rural and piped/urban	Water supply	Floodplain inundation
	Fish/shrimp/crabs (nonrecreational)	Habitat availability and connectivity, food supply	Instream flow regime, floodplain inundation, flows sustaining riparian vegetation
	Fertile land for flood-recession agriculture and grazing	Supply of nutrients and organic matter, moisture conditions in soils	Floodplain inundation
	Wildlife for hunting (nonrecreational)	Habitat availability and connectivity, food supply	Floodplain inundation, flows sustaining riparian vegetation
	Vegetables and fruits	Supply of nutrients and organic matter, seasonality of moisture conditions in soils	Floodplain inundation, flows sustaining riparian vegetation
	Fiber/organic raw material for building/firewood/handicraft	Supply of nutrients and organic matter, seasonality of moisture conditions in soils	Floodplain inundation, flows sustaining riparian vegetation
	Medicine plants	Supply of nutrients and organic matter, seasonality of moisture conditions in soils	Floodplain inundation, flows sustaining riparian vegetation
	Inorganic raw material for construction and industry (gravel, sand, clay)	Sediment supply, transportation and deposition (fluvial geomorphology)	Instream flow magnitude and variability
Regulation	Chemical water quality control (purification capacity)	Denitrification, immobilization, dilution, flushing	Floodplain inundation, instream flow regime
	Physical water quality control	Flushing of solid waste, flushing/retention of sediment, shading	Floodplain inundation, instream flow regime, flows sustaining riparian vegetation
	Flood mitigation	Water retention capacity	Floodplain inundation, flows sustaining riparian vegetation
	Groundwater replenishment (low-flow maintenance)	Groundwater (aquifer) replenishment	Floodplain inundation
	Health control	Flushing of disease vectors	Instream flow regime, water quality
	Pest control	Habitat diversity, disturbance and stress	Instream flow regime
	Erosion control (riverbank/bed and delta dynamics)	Healthy riparian vegetation, erosion, transportation, and deposition of sediments	Flows sustaining riparian vegetation

Continued on next page

Table 1. Comprehensive Checklist of Ecosystem Services Supported by Environmental Flows *(cont.)*

Service category	Service provided	Key flow-related function	Key environmental flow component or indicator
Regulation *(cont.)*	Prevention of saltwater intrusion (salinity control)	Freshwater flow, groundwater replenishment	Instream flow regime
	Prevention of acid sulphate soils development	Groundwater replenishment	Floodplain inundation
	Carbon "trapping" (sequestration)	Accumulation of organic material in peat soils	Floodplain inundation
	Microclimate stabilization	Healthy ecosystems	Floodplain inundation, flows sustaining riparian vegetation
Information	Recreation and tourism (incl. fishing and hunting)	Presence of wildlife, aesthetic significance, good water quality	Site-specific
	Biodiversity conservation	Sustaining ecosystem integrity (habitat diversity and connectivity)	Natural flow regime
	Cultural/religious/historical/ symbolic activities	Site-specific	Site-specific
Life support	The prior existence of healthy ecosystems	All	Natural flow regime

Source: de Groot, R.; Costanza, R; Emerton, L & Bos, E.; Millennium Ecosystem Assessment; Pearce, D., Atkinson, G., Mourato, S., http://www.eflownet.org/viewinfo.cfm?linkcategoryid=4&linkid=21&siteid=1&FuseAction=display, reprinted with permission.

III. THE IMPACT OF HYDROPOWER DAMS ON RIVERS

The degree to which one or multiple hydropower dams will affect a river ecosystem ultimately depends on whether environmental protection and ecosystem services are addressed in the planning, design, and operations of any hydropower scheme. Dams fundamentally change the environmental conditions of a river, both in the part of a river that is being inundated by the reservoir as well as downstream. Dams create barriers for upstream-downstream navigation and movements of fish and other creatures. Dams can also substantially change the flow of water and transport of sediment, nutrients, and food materials that supply downstream aquatic ecosystems and estuaries, with impacts commonly extending for hundreds of kilometers downstream.

Of all the environmental changes caused by dam construction and operation, the alteration of natural water flow regimes downstream of dams has had the most pervasive and damaging effects on river ecosystems. In a comprehensive review of scientific literature focused on the ecological effects of flow alteration, Bunn and Arthington (2002) highlighted four primary impacts:

- River flow shapes physical habitats such as riffles, pools, islands, and bars in rivers and floodplains. Flow alteration can lead to severely modified channel and floodplain habitats, thereby affecting the physical diversity needed to support diverse aquatic communities.
- Many aquatic species depend upon specific water flow conditions during life stages such as reproduction. Flow alteration can impair these biological functions by changing the volume and timing of flow.
- Many species need to move upstream and downstream or from the river to the floodplain during their life cycles. Flow alteration that impairs the fluid connections between these different habitat areas can limit their mobility.
- The invasion of exotic and introduced species in river systems can be facilitated by flow alteration.

Consequences for Ecosystem Service Benefits

All of the dam-induced changes described above have implications for socially-valued ecosystem services, ranging from changes to family farms to the loss of fish stocks that affect an entire community or region. Some of the most common dam-induced impacts include:

- Loss of river fisheries and diminished drinking water quality due to changes in water depth and velocity, water temperature, dissolved oxygen, and nutrient levels.
- Loss of plants and animals used for food, loss of building materials, and diminished floodplain agriculture and grazing due to reduced inundation of wetlands and floodplains.
- Accelerated erosion of channels, islands, and coastal beaches and damage to roads, bridges, farms, and beach tourism areas due to changes in sediment transport.
- Loss of coastal fisheries due to changes in salinity patterns (from reduced freshwater flows).

The increasing focus on poverty alleviation and economic development has been accompanied by a growing recognition of the vital connections between ecosystem services and human well being; as a result, interest in protecting these services has grown. However, the value of such services is not usually captured in economic models, so no consistent financing streams are in place to ensure their protection. Infrastructure projects such as dam development often fail to adequately take them into account.

However, new economic mechanisms involving payments for ecosystem services are being developed and implemented in a number of countries. One approach is allocating some portion of hydropower revenues for use in ecosystem protection or restoration to offset impacts from dams. In addition, some dam plans are incorporating environmental flows and ecosystem service values, but much more needs to be done to take into account the full range of social, economic, and cultural benefits of environmental flows. Box 1 describes an example in eastern Kenya.

Box 1. Valuing Environmental Flows in the Tana River, Kenya

The Tana River runs for 1,000 kilometers through arid and semi-arid eastern Kenya. As the only perennial river in the region, the river's flow supports the livelihoods of more than a million people, including pastoralists, crop farmers, and fisherfolk. The Tana River is also used for hydropower generation, with five existing dams providing nearly 75 percent of Kenya's electricity. Together, the dams have impacted the river's downstream flow and physical characteristics, most notably through decreasing the frequency and magnitude of flooding. According to BirdLife International, two additional dams proposed at Mutonga and Grand Falls would greatly reduce river discharge, silt deposition, and groundwater levels. This would lead directly to the loss of the floodplain forest and the species that it sustains. The livelihoods and well being of the people that rely on the Tana River floodplain for farming, grazing livestock, fishing, tourism, fuelwood, hunting, and gathering foods and medicines would be seriously impacted.

A 1994 valuation study by Lucy Emerton estimated the cost of lost ecosystem services due to the existing dams to be US$27 million, and estimated the incremental costs incurred by building additional dams to be nearly US$20 million. More than one million people have already been affected by the downstream economic losses resulting from the dam-induced changes in the river's flooding regime, with nearly half of these losses borne by one of the poorest segments of the population—nomadic and semi-nomadic pastoralists.

The Emerton valuation study lends strong support to investing in measures that would mitigate or minimize the effects of dam construction on downstream flow (including flood) regimes. Some of the dam design options that had appeared to be unprofitable under a conventional economic cost-benefit analysis actually would yield the highest economic rate of return once environmental costs and benefits were incorporated into the analysis. After considerable debate, a flood and sediment release facility was incorporated into the design of the proposed Low Grand Falls dam. This is intended to release controlled floods and sediment twice a year, around April and November. Mutonga Dam will also have sand-flushing facilities. Although this increases the costs, these costs will be offset by the environmental values. These ameliorative measures are potentially even more valuable in that they might mitigate some of the ecosystem losses—and associated economic costs—resulting from dams already in place on the river.

For more information:

BirdLife International. 2007. BirdLife's online World Bird Database: the site for bird conservation. Version 2.1. Cambridge, UK: BirdLife International. Available at: *http://www.birdlife.org*.

Emerton, Lucy. 1994. *An Economic Valuation of the Costs and Benefits in the Lower Tana Catchment Resulting from Dam Construction*. Report prepared by Acropolis Kenya Ltd. for Nippon Koei, Nairobi.

IUCN. 2003. "Tana River, Kenya: Integrating downstream values into hydropower planning." Case studies in wetland valuation #6. Available at: *http://www.iucn.org/themes/wani/publications/econ/CaseStudy06Tana.pdf*

JICA. 1997. "Feasibility study on Mutonga/Grand Falls Hydropower project." Report to Republic of Kenya, Ministry of Energy, Nairobi, Kenya.

Different Ecosystem Impacts from Different Hydropower Schemes

The impacts of hydropower dams on river ecosystems and associated ecosystem services depend on dam location, design, and operational characteristics, some of which can be chosen and shaped to reduce or eliminate major consequences. Hydroelectric facilities range in size from large dams that generate thousands of megawatts of electricity to supply millions of consumers, to small turbines in rivers generating a few kilowatts that individuals and small industries operate for their own electricity needs or sell to utilities. A hydropower dam scheme may consist of anything from a single dam to a complex system of several dams, reservoirs, power stations, and water transfer infrastructure. The overall purpose(s) of the hydropower dam scheme will largely dictate how it might affect the river ecosystem and opportunities for integrating ecosystem services into the array of benefits to be provided or protected by the scheme. The operating purposes of the hydropower scheme will in turn influence the design of key components, including reservoir size and operational mode, and the location from which water is diverted or released downstream.

Operating Purposes

Dams with multiple objectives have gained considerable appeal because of their ability to serve an array of societal needs and desires. However, designing a dam to serve multiple purposes almost always entails compromise because some purposes inherently conflict with other purposes. For instance, in a hydropower dam project involving a storage reservoir, any removal of water from the reservoir to meet urban or irrigation water supply demands—or managed releases of water from the dam to serve downstream navigation, flood control, pollution dilution, or environmental flow needs—will constrain hydropower operations.

The challenges of operating a hydropower scheme to serve both hydropower and flood control purposes deserve special attention here, both because of the growing popularity of such projects as well as their potential to cause significant disruption of river ecosystems resulting from substantial alteration of natural flow regimes. When a dam is being used for both hydropower and flood control, the standard approach is to maintain high reservoir levels during the non-flood season to maximize hydropower generation, and then lower reservoir levels at the onset of the flood season to create storage for capturing floodwaters. The lowering of reservoir levels usually requires the release of a substantial volume of water during a time of year when natural river levels may have been quite low. Similarly, at the end of the flood season, reservoir levels are raised so that hydropower production can be maximized. This requires capture of a substantial volume of water in the reservoir with little release to the downstream river ecosystem. These transitions can be extremely disruptive of natural flow regimes, with serious consequences for ecosystem health and traditional human uses of the river and floodplain. As discussed in Section V, these problems may be ameliorated considerably by using natural floodplain storage to its maximum potential, thereby reducing the amount of flood storage required in a dam scheme with multiple objectives.

Reservoir Size

Virtually every hydropower dam will cause water in the river to become impounded, forming a reservoir. However, the volume of water that is impounded or stored—and the way in which this stored water is used in the generation of hydropower or for meeting other project goals—can differ greatly. The size of the reservoir will in many cases dictate how much benefit—such as hydropower generation or water supply—can be achieved by the project, and it can also determine the timing of when those benefits can be generated. For instance, Lake Powell on the Colorado River in the western United States can store the equivalent of three year's worth of average annual runoff. This immense volume of stored water may be released for hydropower generation or water supply months or even years after it is captured in the reservoir. As a general rule for multi-objective dam schemes, the larger the reservoir, the greater the economic benefits that can be generated and the greater the flexibility in timing the delivery of those benefits.

The benefits of large reservoirs can come at great cost to other social benefits and livelihoods, particularly those tied to ecosystem services. Large reservoirs inundate large areas of land and many kilometers of river, and thereby displace existing uses of the land and river. Water is stored in reservoirs during times of heavy precipitation or runoff and then released according to varying demands for electricity, water supplies, and other purposes. These energy and water demands follow seasonal, daily, and hourly trends that are unrelated to the life cycles of river species and the timing of other natural processes that sustain river health. For example, a primary goal of reservoir operations during anticipated periods of high runoff might be to maintain sufficient vacant storage space in the reservoir to capture the incoming flood, or to avoid "spilling" water that could otherwise be used to generate electricity. By capturing these high water flows, the downstream ecosystem will receive less water, affecting the nourishment of floodplain vegetation or wetlands (which may be important for agricultural or grazing uses or fiber production, or cleansing the water), or decreasing opportunities for fish to feed and spawn on floodplains.

Reservoir size can also substantially affect a hydropower project's ability to meet multiple objectives during times of low water flows. Using water stored in the reservoir, dam managers may be able to continue to meet a variety of water and energy needs, even during droughts. These needs may include providing adequate environmental flows to sustain downstream ecosystem services. However, if reservoir storage is inadequate during dry periods, operators will face especially difficult choices in managing across environmental, electricity generation, or water supply demands. Additionally, in an effort to generate hydropower at the dam during dry periods, or to release larger volumes of water from the reservoir to support downstream irrigation, navigation, or pollution dilution, river flows downstream from dams can become artificially augmented to the point that they disrupt life cycles and other natural processes in the ecosystem. In other words, it is not always the case that "more water is better" for the ecosystem. Environmental flow releases from dams need to be tailored such that adequate habitat conditions and associated ecosystem services are sustained in all seasons and years, both wet and dry.

Operating Mode

The hour-to-hour, day-to-day, and seasonal electricity generation pattern of a hydropower scheme will influence the water releases from a dam. The power generation pattern of a hydropower station depends on its role in the electricity system. There are essentially three basic operating modes:

- Base-load generation serves a more or less steady (base) level of electricity demand during a day so that the release pattern downstream is at a steady continuous flow.
- Peak load generation serves peak power demands (typically morning and evening peaks), creating a pattern of high releases when generating electricity and, if water is in short supply, little or no release at other times (for example, at night).
- Load following (automatic generation control) involves generating power in a manner that follows minute-by-minute variations in demand for electricity. A portion of the system power requirement is assigned to specific generating units that are particularly suited to this function. Flows from these dams fluctuate throughout the day.

Each of these operating modes will affect downstream flows to varying degrees. However, each of these standard modes of operation can be modified to make them more compatible with environmental flow needs. For example, if alternative power sources are available, limits can be placed on the range within which flow releases from a dam can fluctuate from hour to hour, or day to day. A minimum flow release requirement can be established to prevent the hydropower dam from shutting off all downstream flow when electricity is not being generated. A maximum release during normal (non-flood) operations can also be set so that high flow releases during peak power production do not damage downstream ecosystems or human settlements. Additionally, individual hydropower dams can be operated in multiple modes simultaneously, or the multiple dams comprising a cascade on a river can each be operated in different modes to help align dam operations with environmental flow needs downstream.

A hydropower dam will be least disruptive to a river's flow regime when it operates as a "run-of-the-river" facility, with outflows essentially matching the natural regime of inflows. A run-of-the-river operation in its truest form would release water hour by hour at the same rate as inflows; such operations are typical of small hydropower dams with little to no storage available to modify inflows. Some hydropower dams may operate so that *averaged* outflows match inflows on a daily or even a weekly basis. Within a given day, the flow releases may deviate considerably from the natural inflow regime, which can disrupt downstream ecosystems.

Diversions and Location of Downstream Flow Release

Some hydropower schemes are designed to divert water at a (usually smaller) dam and convey it to a point downstream, or even to another river basin, where it is passed through turbines at a power station to generate electricity before returning to the river channel. On small rivers, except during floods, the diversion may take most or all of the river flow.

These diversion facilities present many of the same challenges for ecosystem protection as other types of hydropower schemes. But they add another very significant complication for the section of river that is being bypassed by the diversion. The environmental flows needed to support ecosystem services in the affected river need to be integrated into the design and operation of the hydropower diversion facility. This challenge is usually addressed by setting different ecosystem protection goals for the bypass reach and the river section downstream of the eventual flow release from the power station.

Key Points

- Not all hydropower schemes are alike, or have similar impacts on downstream ecosystems. They differ greatly in terms of their storage capacity and operational mode, and may or may not involve a diversion of water out of the river.
- Each of the physical components and operational plans for a hydropower dam scheme is designed to meet specific objectives, including environmental flow needs. Tradeoffs and compromises in societal needs and values are involved in designing and operating dams for multiple purposes.
- Dams can be operated to accommodate environmental flows and other ecosystem processes to achieve ecosystem-related objectives expressed by stakeholders.

IV. REGIONAL OPPORTUNITIES FOR INTEGRATING ENVIRONMENTAL FLOWS

Many opportunities exist for integrating ecosystem service values and associated environmental flow needs into water and energy development processes. Such integration will help to minimize cultural disruption and the loss of existing social values tied to ecosystem services when new dam projects are being developed.

In presenting options for integrating environmental flows into hydropower development plans, this technical note focuses on two scales: (1) a regional scale, which includes regional or national plans and can encompass many river basins and even multiple countries; and (2) a local scale, which is usually restricted to a single river basin or hydropower dam scheme. While somewhat arbitrary and overlapping, differentiating between these two scales is convenient for discussing the array of options for integrating environmental flows. For instance, decisions about the number and types of hydropower dams to be used, and their geographical siting—including decisions about whether to allow hydropower development in certain river basins—are generally made as part of a *regional* planning process. Examples of such regional-scale plans would include the energy planning being conducted by the Volta Basin Authority for countries in West Africa, the "Plan Puebla a Panama" being conducted in Central America, the National Energy Grid of Brazil, and the work of the Mekong River Commission. On the other hand, decisions such as reservoir and turbine sizing for specific dams, or the operational mode and dam operating plan to be employed, are usually made when designing a specific hydropower scheme at the *local* level.

Regional and local planning efforts need to be highly integrated to generate or protect social values in an optimal manner, whether those benefits are tied to dam operations or environmental flows that sustain healthy river ecosystems. The options for integrating environmental flows into local hydropower development plans can either be enabled or constrained by regional plans. For instance, the opportunity to operate any particular dam as a run-of-the-river facility that minimally alters river flows—rather than in a peaking mode that could seriously disrupt flows—might depend greatly upon decisions made during a regional planning process in which the role of various power generators feeding into an electrical grid are defined. Furthermore, the ability to adjust targets for power or revenue generation at any individual dam is far greater at a grid-level or regional scale than in the design of any single dam.

Regional Scale Hydropower Planning Considerations

Decisions made during the earliest phases of a regional energy plan can have substantial influence on the prospects for integrating ecosystem-related goals (including ecosystem services tied to environmental flows) into the operations of any of the hydropower dams to be included in a regional energy system. When ecosystem services and requisite environmental flows are adequately considered in a regional plan, it will be far easier for any individual hydropower scheme to address those ecological considerations because appropriate energy policies and broad-scale design parameters will already have been set by the regional plan (Box 2). Additionally, the costs and difficulties of mitigating the environmental impacts of individual dams or cascades of dams on a river will be lessened. On the other hand, if regional plans do not exist or do not adequately address these ecological considerations, designers will have less public guidance to accommodate environmental flows in individual projects and so will be constrained by predetermined power demand targets and water availability in the local watershed.

Given the tradeoffs inherent in assessing various energy options and developing national or regional energy policies, as well as the need for broad stakeholder involvement in these decisions, regional planning and energy policy development is ultimately the responsibility of governments in consultation with a full range of private and public stakeholders.

Developing Regional Energy Plans

Regional plans can facilitate environmental protection in some important ways, including the following:

- *Projecting regional energy demands*. By maximizing "demand-side" strategies, the need for new power generation facilities can be minimized.
- *Developing objectives for ecosystem services and biodiversity protection*. Early identification of socially important species and ecosystem services, and setting objectives for their protection, will help planners integrate these concerns into development plans.
- *Clarifying energy development policies*. When governments provide clear guidance on the environmental values to be conserved, responsibility for mitigation costs, and rivers to be protected from development, energy developers will benefit from improved certainty in the development process and environmental values will be better protected.

Box 2. Balancing Development and Protection in Regional Planning: The State of Maine's Comprehensive Hydropower Plan

In the early 1980s, the state of Maine in the northeast United States experienced an energy crisis. The state had become heavily dependent on imported oil for its energy needs, and international embargoes and attendant price increases threatened to cripple the state's economy. Hydropower became very attractive as a more secure and less expensive source of electricity. At the same time, changes in federal law created financial incentives for hydropower development, leading to a flood of proposals for new dams. However, the fishing industry became alarmed at this surge in dam proposals, viewing them as a serious threat to salmon fisheries.

In response, Governor Joseph Brennan set in motion a series of planning and policy development initiatives. In 1981, he issued a Maine Energy Policy that acknowledged the importance of hydropower in meeting a portion of the state's energy needs, and called for the removal of unnecessary administrative obstacles that were impeding the permitting of favorable hydropower projects. The governor directed the Office of Energy Resources to assess the state's future energy needs, which identified needs for an additional 340 megawatts of hydropower, equivalent to a hydropower increase of more than 50 percent.

At the same time, the governor initiated steps to protect other values afforded by Maine's rivers for commerce and public enjoyment. He ordered the state's fishery agency to develop a new statewide fisheries management plan. He also directed Maine's Department of Conservation to identify rivers with outstanding natural and recreational values, resulting in the 1982 Maine Rivers Study. On the basis of this study, the governor issued an executive order designating one-third of the state's rivers for special protection. This order prohibited the construction of new dams on the protected rivers, and required modification of existing dams to enhance river health.

The long-lasting benefits of Maine's energy and river protection policies are summarized in a paper entitled *The Maine Rivers Policy*.

The thread that unites the many diverse planning and implementation actions in the Maine Rivers Policy is balance. It does not call for sacrificing economic growth for the sake of preservation. On the contrary, by assessing Maine's long-range need for hydropower, carefully weighing the demands on Maine's rivers, identifying the best uses for individual river segments, and providing means to resolve conflicts, this policy recognizes that all of the beneficial uses may be integrated harmoniously on Maine's vast and diverse river resources.

Without clear guidance about those Maine rivers where hydropower is not desirable, developers had wasted valuable time and money on projects that never would be built. This situation is familiar throughout the nation. With the direction provided by the Maine Rivers Policy, developers can now focus their efforts where hydropower is less likely to present insurmountable problems.

For more information:

Sullivan, Mark and R. Alec Giffen. 1985. "The Maine Rivers Policy." Paper presented at the Symposium on Small Hydropower and Fisheries, Denver, Colorado, May 1–3, 1985.

Regional Scale or Strategic Environmental Assessment

There are many ways to avoid or mitigate the impacts of hydropower development on river ecosystems and human livelihoods, but these approaches need to be custom-tailored to the needs, challenges, cultural contexts, and biological and physical settings of each region. Regional environmental assessments (commonly referred to in the hydropower industry as *strategic environmental assessments*) can help avoid or lessen impacts to ecosystem services from hydropower development by addressing the following considerations:

- *Determining environmental flow needs*. When environmental flow needs throughout a region have been defined, decisions about where to locate dams, as well as their design and operation, can be made in a manner that is most compatible with ecosystem-related objectives. New approaches are now available for determining environmental flow needs at a regional scale (Box 3).
- *Identifying hydropower dam locations*. New hydropower dams should be designed and sited in a manner that minimizes their regional ecological and social impacts while meeting power generation and other social and economic objectives.

Box 3. The Ecological Limits of Hydrologic Alteration (ELOHA): A Framework for Determining Regional Environmental Flow Needs

The cost and time required for determining environmental flow needs for individual rivers, and the lack of a scientifically credible approach for scaling up site-specific studies or information into regional generalizations, has long hampered the integration of ecosystem protection into integrated water resource management and energy development plans. The Ecological Limits of Hydrologic Alteration (ELOHA) method has been designed to overcome these challenges. ELOHA applies knowledge gained from river-specific studies to regions as large as states, provinces, nations, or large river basins, without requiring detailed, site-specific hydrologic or biological information for every river. ELOHA synthesizes available hydrologic and biological data from rivers within a region to produce coarse-scale estimates of environmental flow needs that will be useful in regional water and energy planning.

For more information:

http://*www.nature.org/initiatives/freshwater/ELOHA*

Regional Scale Hydropower Design Options

When attempting to integrate environmental flow needs into a regional hydropower development plan, the coordinated design and operations of multiple hydropower dams—such as those connected in a regional grid system—can open up considerable flexibility and enable optimal protection of ecosystem services across a region. The following design opportunities need to be considered in regional scale planning.

Power Grid Interconnection

Water is the ultimate constraint on a hydropower dam operator's ability to provide environmental flow releases while meeting electricity demands. However, when other (non-hydro) generating sources are available to meet electricity demands within a grid system, the role of hydropower dams may become less constrained. Additionally, in many regions, grid systems are sufficiently expansive geographically that they incorporate hydropower dams on rivers of different sizes, many of which may be experiencing different hydrologic conditions at a given time. Through coordinated grid operations, the flexibility inherent in managing multiple types and sources of power generation can create opportunities to integrate environmental flow needs.

Three specific considerations deserve attention in designing or improving a regional grid system. First, consider how much of the base-load electricity demand in the system can be met by operating hydropower dams as close to run-of-the-river as possible. From the perspective of minimally altering river flows, a broad objective is to enable hydropower dams to be operated in rhythm with the rainfall and runoff in the watershed, rather than dictated solely by the power demands of the grid. Maximizing hydropower potential throughout the grid system while operating as close to run-of-the-river as possible will require that turbines, generators, and transmission lines are sized such that they can efficiently use as much or as little of the river flow as is available (and safe from a flood risk perspective) at each dam in the system.

Second, consider whether other generating sources—particularly gas-fired or other thermal sources—can be used to partially or completely offset the need to use hydropower dams to meet peak demands, and at what cost to the system. Minimizing the need for hydropower during peak periods will reduce the need to alter flow regimes. As previously noted, the design and implementation of environmental flows is not an all-or-nothing decision. In moving toward run-of-the-river operations to improve environmental flows and associated benefits, the tradeoffs in power generation, and more specifically the benefits of using hydropower for peaking, must be carefully evaluated. By assessing multiple dams and other generating sources within an energy system, it may become possible to move further toward run-of-the-river operations at the dams that are of greatest ecological importance, while maximizing peak power generation at dams that are of lesser ecological concern.

Third, consider the amount of reservoir storage necessary to fill in the gaps in the electricity production system to meet both base load and peak demands, particularly under drought conditions. When water stored in a reservoir is used to generate hydropower, the rate of water discharged from the dam can differ considerably from the rate of reservoir inflows. These differences need to be minimized whenever possible to protect downstream river ecosystems. Storage reservoirs can be operated as run-of-the-river facilities during normal (non-drought or non-peak demand) periods by maintaining high water levels in the reservoir and dropping into the available water storage only when necessary. Maintaining high water levels further helps to maximize the overall power output from the dam due to increased hydraulic head.

In many interconnected systems, hydropower has unique flexibility to meet peak demands as well as perform other system stability services relative to other sources of generation. For example, thermal plants incur higher costs in shutting down and starting up, and have their own set of environmental consequences (e.g., air emissions, water quality). System-wide benefits and costs—covering economic, environmental, and social consequences—must be taken into account when managing flows at individual hydropower plants.

Coordinated Operations of Dam Cascades

In many rivers around the world, *cascades* of hydropower dams have been constructed or are being planned. Often the operations of these cascades is not fully integrated or optimized for either hydropower generation or environmental flow performance. This may be due to the fact that more than one entity owns the dams in the cascade, or the computational skills or technologies necessary to achieve a high level of optimization have not been used. Investment in a computer-based decision support system is one of the most cost-effective ways to optimize the performance of a multi-dam hydropower system. When environmental flow criteria such as minimizing alterations of the existing flow regime are included in the optimization strategy, the considerable flexibility in a multi-dam operation can be effectively tapped for environmental flow protection or restoration.

When more than one hydropower dam is built on a river, or on multiple rivers within a region or large river basin, opportunities for modifying the function of any one dam will likely be increased considerably. For example, in a cascade of hydropower dams on the same river, power generation can be maximized at upstream dams to enable lower dams to serve more of a re-regulating function, thereby minimizing flow alterations in the downstream river. In a cascade of closely stacked reservoirs with little flowing water in-between, the ecological health and ecosystem services in upper portions of the cascade may have already been so compromised that it would do little additional harm to generate more power at the upper dams. Similarly, when dams are located on more than one river but supplying power to the same location(s), electricity generation and flow alterations can either be balanced among multiple dams or impacts can be traded off to provide more flow restoration to the highest-priority rivers with the greatest environmental needs.

Key Points

- Societal objectives for dam development will be best met when regional energy plans—which set broad regional, national and/or river basin objectives for water and energy development and environmental protection—are paired with more detailed local-scale environmental assessments for individual dams or cascades of dams on specific rivers.
- Because of the tradeoffs inherent in assessing various energy options and developing national or regional energy policies and the need for broad stakeholder involvement in these decisions, regional energy planning and energy policy formulation should be a government responsibility.
- Regional planning can facilitate environmental protection by giving due consideration to demand-side strategies to reduce the need for additional power sources, setting objectives for biodiversity and ecosystem service protection, and clarifying who will bear the costs of environmental mitigation.
- Regional or strategic environmental assessments can facilitate environmental protection by determining environmental flow needs for the region's rivers, and identifying dam locations that will have the least impact on sensitive species, ecological processes, and ecosystem services.
- Investment in computer-based decision support and hydrologic forecasting systems are among the most cost-effective ways to optimize the performance of a multi-dam hydropower system. When environmental flow criteria such as minimizing alterations of the existing flow regime are included in the optimization scheme, the considerable flexibility in a multi-dam operation can be effectively tapped for environmental flow restoration.

V. LOCAL-SCALE OPPORTUNITIES FOR INTEGRATING ENVIRONMENTAL FLOWS

The regional planning process described in the preceding section sets the context for attaining water management and stakeholder objectives within a region. For example, through its assessment of options and tradeoffs, a regional energy plan identifies which rivers will be developed for hydropower generation, and sets target levels of power production and other objectives for each river basin, including the degree to which ecosystem services and biodiversity are to be protected. When regional planning is conducted with adequate public participation and communication, dam developers will be much better able to design, construct, and operate individual dams in a manner consistent with societal goals. At the same time, considerable flexibility may be available in the design and operation of individual facilities.

Many options and approaches are available for designing and operating new or existing hydropower dams, or cascades of dams, in a manner that minimizes or reduces their impacts on river ecosystems and associated ecosystem services. In this section, we discuss local-scale planning considerations in the context of environmental impact assessments. The section then turns to a variety of options for designing and operating individual dams or cascades of dams in a manner that is compatible with ecosystem-related goals.

Local-Scale Environmental Impact Assessments

The following considerations need to be addressed at the local scale to supplement—and align with—decisions made at the regional scale.

Scoping of Social and Ecological Concerns and Values

Stakeholder values affected by dam development may include concerns directly tied to specific ecosystem conditions that can be affected by environmental flows, such as: populations of fish that are harvested commercially or for subsistence purposes; the need for floods to regenerate forage or building materials in floodplain areas; prevention of disease outbreaks; protection of endangered species; flood control; and recreation and tourism. The stakeholder engagement process can be used as a means for gathering valuable information pertinent to environmental flow needs, particularly in data-poor countries (Box 4). The timing of stakeholder engagement is also important. Stakeholder involvement works best when it is done early in the process. Much greater discussion of stakeholder considerations is provided in a World Bank publication entitled *Stakeholder Involvement in Options Assessment: Promoting Dialogue in Meeting Water and Energy Needs*.

Tradeoff Analysis

A fundamental goal of all dam projects is to maximize overall development benefits, encompassing economic, social, and environmental impacts. In an ideal situation, the full spectrum of potential benefits and impacts from dam development would be well understood. Their economic, cultural, or ecological consequences would be defined with some certainty, and all of the affected individuals would be identified. With such a knowledge base, a thorough and objective tradeoff analysis could be conducted to support the planning and decision-making processes involved in a dam project.

In reality, it can be quite difficult to identify all of the parties that will be affected by a development project and to engage them or their representatives in a stakeholder dialogue to reveal their needs and values. Scientific ability to predict the specific ecosystem changes likely to occur in response to dam development and operation remains quite limited. The economic valuation of ecosystem services is still in its infancy. Ethical dilemmas arise in comparing the lost benefits of local communities dependent upon the goods and services provided by a natural river—many of which are difficult to quantify monetarily—with the quantifiable benefits of project development to be realized by other individuals who might live some distance from the affected river and local communities. In short, the data and techniques required to conduct a comprehensive and objective tradeoff analysis remain quite limited.

It is therefore not surprising that dam development proposals often generate considerable controversy. Given that there is no single right way to resolve these issues in all places, the best course may be to follow a few best-practice standards. The following are suggested as a starting point:

- Orchestrate a thorough and inclusive dialogue that encourages full expression of stakeholder concerns, needs, and values, such as described in the World Bank's stakeholder document cited in the preceding section. In particular, identify river-dependent plant and animal species—or processes such as annual flooding of agricultural or grazing areas in floodplains—that are of considerable economic or cultural importance to local communities.
- Conduct an assessment of the environmental flows needed to sustain key ecosystem components and processes, with particular attention to the plants, animals, and ecological processes of greatest importance to local communities. Further guidance on appropriate environmental flow assessment methods is provided later in this section and in the publications cited in Annex 1 on "Recommended Reading."
- Conduct an engineering analysis of various options for dam design and operation to gain an understanding of the potential tradeoffs among infrastructure costs, changes in hydropower production (and other dam-related benefits), and provision of environmental flow releases. This analysis should fully consider the options for dam design and operation discussed later in this section.
- Thoroughly communicate the results of the tradeoff analysis with stakeholders and use these dialogues as a basis for decision-making.
- If the selected option is expected to cause significant social or environmental impacts, stakeholder compensation and mitigation can be incorporated into the stakeholder dialogue and the project design. For example, investments to improve habitat conditions—such as water quality improvements or setting back levees to reactivate floodplain areas—may help to increase the productivity of fisheries and offset losses of other ecosystem goods or services.
- When the project is built and begins operation, monitor all aspects of the ecosystem and economic or social conditions identified as being of critical importance to local communities to verify that the intended protection of ecosystem-related values is being achieved. Additional guidance on "adaptive management" of dam projects is provided in Section VII.

Specifying Objectives for Dam Management

The collective social, environmental, and economic values of stakeholders, political leaders, and dam managers can be integrated explicitly into a dam development project. It is useful to set objectives with specific targets that can be quantified and measured directly. It is also important to define some objectives that can be achieved almost immediately. These short-term results can be very helpful in gaining public support and fostering learning about management approaches necessary to attain objectives.

Developing River-specific Environmental Flow Recommendations

Regional estimates for estimating environmental flow needs are essential in designing a regional hydropower system that is compatible with regional goals for biodiversity and ecosystem service

Box 4. Using Indigenous Knowledge in Assessing Environmental Flow Needs: Rio Patuca, Honduras

Demand for electricity is growing rapidly in Honduras. Currently, 70 percent of electricity is generated from relatively expensive—and polluting—oil and coal plants. With most of the nation's hydropower potential still undeveloped, Honduras has decided to construct a hydropower dam on the Rio Patuca, the country's longest river and the third longest river in Central America.

While the upper watershed has been largely deforested for cattle ranching, the Patuca's lower reach passes through a region of immense cultural and biological value. Three protected areas flank the river's course and dozens of communities of the Tawaka, Miskito, and Pech peoples line its banks. The river provides important ecosystem services to these communities, including fisheries that serve as a major source of protein, and sediment deposition during annual flooding that improves the fertility of low-lying agricultural fields. Further, the river is the primary means of transportation in this roadless region. The lower Patuca basin is part of the largest tropical forest north of the Amazon, which supports extremely high species richness.

Because the local communities and river ecosystem depend strongly on the Patuca's flow regime, the Empresa Nacional de Energía Eléctrica (ENEE), the Honduran energy agency, asked TNC to provide guidance on a flow regime below the proposed dam that would maintain the river's biodiversity and ecosystem services. Due to a paucity of technical data and expertise, TNC used traditional ecological knowledge about fisheries, agriculture and transportation, derived from the communities along the river, as the basis for flow recommendations.

Community members provided information on flow levels through two sources of spatial information: cross-sectional surveys of the river and hand-drawn maps of each community. This information was synthesized with other regional information to develop conceptual models of the linkages between flows and important fish species. These sources of information, augmented by a hydrological analysis of a 30-year record of daily flows, provided a foundation for two stakeholder workshops during which participants—ranging from agency scientists to indigenous community members—developed a recommended flow regime.

For more information:

http://www.nature.org/initiatives/freshwater/files/final_patuca_case_study_low_res_new_logo.pdf

protection. However, these regional estimates will need to be further refined as part of a local-scale environmental assessment, typically referred to as an *environmental impact assessment* (EIA) in the hydropower industry.

Many excellent methods and tools for site-specific evaluation of environmental flow needs have been developed in recent decades. These approaches involve in-depth, localized assessments of environmental flow needs for specific rivers or segments of rivers, such as below dams, and should be included in environmental impact assessments for individual dams or cascades of dams on a river. These site-specific methods are included in the recommended reading materials in Annex 1 of this note, which include the World Bank series of technical notes on environmental flows.

The integration of ecosystem-related objectives into dam designs and operations will involve tradeoffs between various dam development goals and changes in existing conditions, usually including the need to modify the historical flow regime to some extent. Therefore, the characteristics of the historical flow regime necessary to meet ecosystem-related goals specified through the stakeholder process described above needs to be carefully considered in an environmental impact assessment.

Box 5 and Figure 2 provide an example of an environmental flow assessment conducted for the Savannah River in the United States, where a cascade of dams is operated for multiple purposes, including hydropower generation. This case study shows that important ecosystem-related objectives can be met by providing carefully tailored low-flow and high-flow releases at specified times and for particular durations.

Box 5. Environmental Flow Assessment for the Savannah River, U.S.A.

In 2002, the U.S. Army Corps of Engineers initiated a Comprehensive River Basin Plan for the Savannah River in the states of Georgia and South Carolina. A major objective was to assess the degree to which various human needs and values for the river might warrant changes in the Corps' dam operations.

The Corps asked scientists at TNC to help facilitate a process for developing flow recommendations in collaboration with the University of Georgia's River Science and Policy Center. This resulted in a summary of knowledge about the linkages between flow variations and the life cycles of numerous plant and animal species, as well as a set of conceptual models illustrating these connections and human influences on key flow characteristics. In a workshop, scientists specified detailed flow requirements for a long list of target species and for maintaining key ecosystem processes such as salinity regimes in the estuary to support important ecosystem services such as fisheries production. The resulting flow recommendations differ among wet, average, and dry water years, and differ according to three different sections of the river: Augusta Shoals, Floodplain Reach, and Estuary (Figure 2).

This process took place over a nine-month period and cost US$75,000, primarily for the literature review and summary report. Many scientists participated without cost as part of their regular job duties.

For more information:

Richter, B.D., A.T. Warner, J.L. Meyer, and K. Lutz. 2006. "A collaborative and adaptive process for developing environmental flow recommendations." River Research and Applications 22: 297–318.

Dam Designs and Operational Plans to Facilitate Environmental Flow Releases

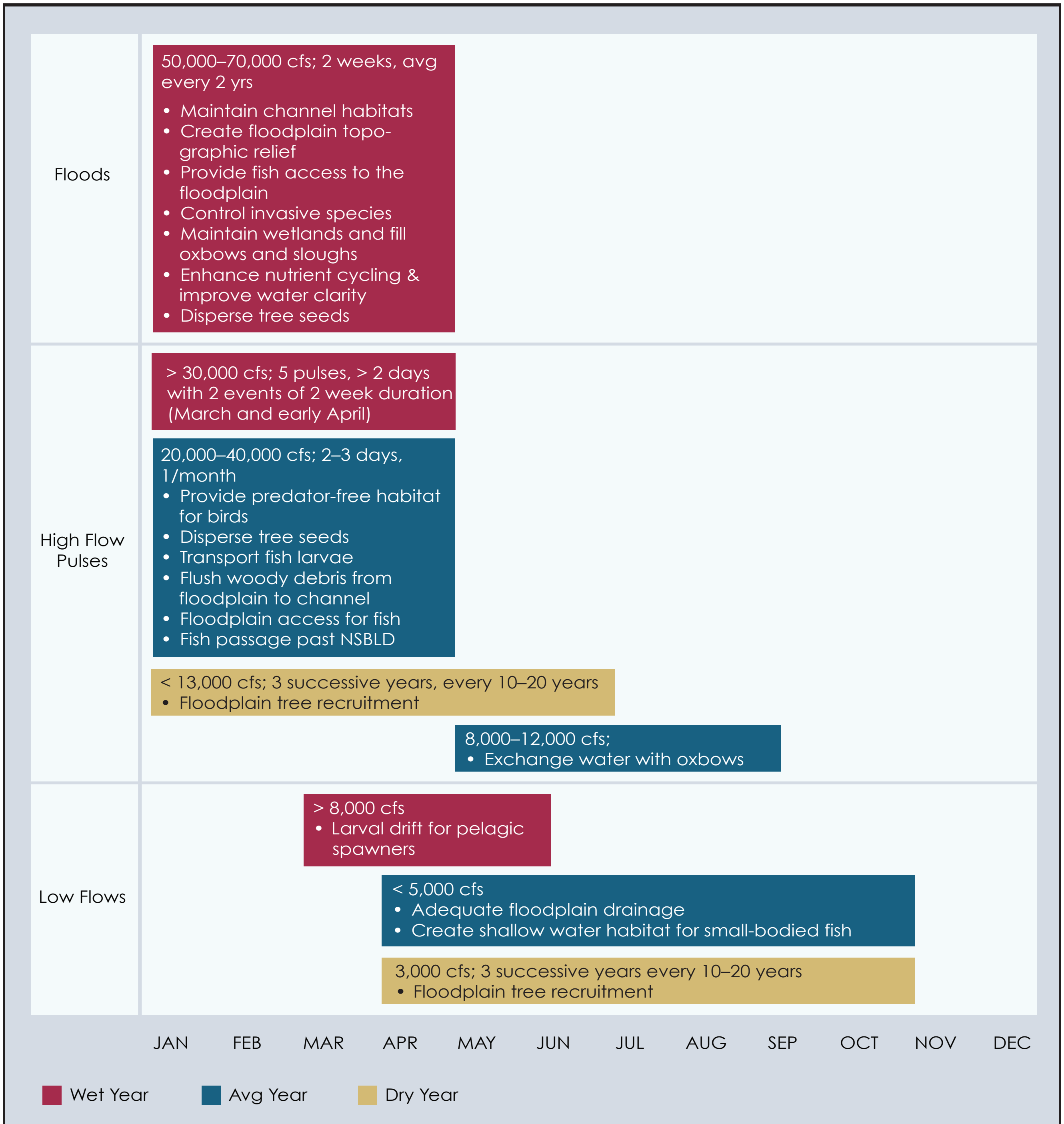
Dam projects with multiple objectives require balancing of operations to meet continually fluctuating energy demands and water supplies as well as changing social priorities and environmental conditions. Climate change will exacerbate these challenges over the longer term. Designs that can accommodate flexible operations will be more effective over the long term.

Four hydropower project design considerations that can provide considerable flexibility for meeting environmental flow needs are highlighted here: (1) flood management using floodplain storage; (2) variable outlet and turbine-generator capacities; (3) multi-level, selective withdrawal outlet structures; and (4) re-regulation reservoirs. The latter three involve considerations for dam design, whereas the first requires management of floodplain areas downstream of the dam. Incorporating these features in the original design of a hydropower project will be far less costly than retrofitting later.

Flood Management in Floodplains

Dams operated for both hydropower generation and flood control can substantially impact river ecosystems if environmental flow needs are not explicitly integrated into project design and operation. These problems can be reduced or avoided by maximally using natural floodplains for flood management. By storing some portion of floodwaters on the floodplain instead of in a reservoir, the total volume of necessary flood storage space in the reservoir can be reduced. In many instances, a "triple-win" solution may be available. By protecting or reactivating downstream floodplain areas or allowing agricultural areas to be flooded occasionally, the flood storage requirement in the upstream reservoir(s) can often be reduced substantially and reallocated for hydropower use, additional water supply, or improved environmental flows downstream of the dam. Reflooding of natural floodplains can bring substantial ecological benefits as well, such as providing additional spawning and feeding opportunities for fish and enabling the floodwaters to fertilize and moisten floodplain areas used for agriculture or grazing. The challenge of achieving these multiple wins—gaining hydropower capacity, reducing overall flood risk, and improving environmental flows—is the realignment of land use, in particular moving structures and human settlements out of the floodplain and addressing agricultural losses during flood events.

Figure 2. Environmental Flow Recommendations Developed for the Savannah River, U.S.



Source: Richter et al. 2006. Copyright John Wiley & Sons Limited. Reproduced with permission.

Variable Outlet and Turbine-Generator Capacities

The ability of a dam operator to provide a range of flows for downstream environmental purposes is ultimately dependent upon a dam's outlet and turbine-generator capacities. Many hydropower dams lack adequate turbine-generator capacity to make large releases, such as controlled floods that may be highly desirable for maintaining the ecological health of downstream floodplain ecosystems and estuaries, without sacrificing power generation. Because of these constraints, some fraction of controlled flood discharges must be released through the dam's flood spillway. This sacrifice of power generation causes dam operators to resist such controlled flood releases. This is the situation at the Manantali Dam in the Senegal River basin. At that dam, some 2000 m^3/sec of water would need to be released to inundate the floodplain to support 50,000 hectares of recessional agricultural production, yet the outlet and turbine-generator capacity is only 480 m^3/sec. The rest of the required flow would need to be released through the spillway, thereby compromising hydropower generation. Necessary structural modifications to expand the powerhouse capacity from 480 to 2000 m^3/sec would be very expensive at this point, but had the powerhouse capacity and reservoir storage tradeoff been optimized in the first place, the economics of providing floodplain inundation would likely have been more favorable. At Manantali, as at many hydropower dams, it is difficult and expensive—and often impractical—to retrofit the dam with additional turbine-generator units after the dam has been built.

Ecological problems can also arise when flow releases change rapidly up or down (called *ramping*). Ecologically damaging ramping occurs when a dam suddenly begins spilling high volumes of water during a flood, or when substantially greater volumes of water are released when additional turbines are activated. This can lead to high mortalities in fish and other animals in the river or on the floodplain or cause undesirable erosion and sedimentation problems downstream. Conversely, when releases from a hydropower dam are being reduced for the purposes of rebuilding water levels (head) in a storage reservoir by shutting down outlets, river flows can be curtailed too abruptly and leave less-mobile animals such as mussels and small fish and their eggs high and dry at the river's edge. Providing a gradation in turbine-generator sizes and reservoir outlets in a dam's design will minimize problems with these flow transitions. Further, construction of re-regulating dams downstream of a hydropower dam can catch and partially even out fluctuations by releasing water in run-of-the-river fashion.

When designing the outlet and turbine-generator capacity of a new dam, it is highly desirable to incorporate a wide range of water release capabilities whenever feasible, as well as adequate transmission capacity to convey the electricity, so that the full array of dam operating objectives—ranging from hydropower generation to environmental flow releases—can be accommodated. By providing a range of outlet sizes, such as incorporating multiple turbine-generator units of varying sizes, dam operators will be able to meet a variety of dam operating objectives.

Multi-level (Selective Withdrawal) Outlet Structures

The water in many reservoirs can become stratified during certain times or throughout the year, which can lead to considerable differences in water temperature with depth in the reservoir. Water near the bottom of a reservoir may contain very little dissolved oxygen. This anoxic condition can cause chemical reactions that lead to undesirable water quality conditions in deep water zones. Both of these conditions can create serious problems for fish and other aquatic animals downstream of the dam. Therefore, the suitability of dam releases to support aquatic life and other uses downstream can be substantially affected by the depth at which that water is released from the reservoir. Multi-level outlet structures (also called *selective withdrawal* structures) can be constructed to provide dam operators the flexibility to release water from different reservoir levels, depending upon the time of year, differences in water quality and temperature, and downstream management objectives (Box 6).

Re-regulation Reservoirs

The impacts of hydropower generation on natural river flows can be mitigated to some degree by constructing a re-regulating dam, usually built immediately downstream of the lowermost hydropower dam. The re-regulating dam can be operated to smooth out the unnatural fluctuations

Box 6. Multi-level Release Structure Benefits Salmon in Sacramento River in California, U.S.A.

Beginning in 1987, the U.S. Bureau of Reclamation was asked by fishery agencies to help improve the water quality in the Sacramento River to restore salmon habitat. The operations of Shasta Dam caused dam releases to be too warm for salmon to reproduce. Initially, dam operators began regulating downstream water temperatures by releasing water through the river outlet works. These releases bypassed the power plant, reducing hydroelectric generation, and costing about US$63 million in replacement power during the 10 years between 1987 and 1996.

In 1989, Reclamation engineers designed a multi-level intake structure to be installed in Shasta Dam. This "temperature control device" allows dam operators to meet federal and state water temperature requirements for salmon habitat in a 100-kilometer reach of the Sacramento River.

To conserve the cold water in Shasta Lake, withdrawals are made from the highest elevation possible while meeting the downstream water temperature targets. During the spring, when the temperature of the surface water is coolest, operators release water from the highest level of the temperature control device. During the summer and fall, when surface water has warmed, water is withdrawn through the device from mid- and low-level intakes. Reclamation engineers have analyzed the multi-level intake structure's performance for three years, concluding that the structure is performing as desired.

For more information:

Vermeyen, T.B. 2003. "Providing California Hydropower While Improving Salmon Habitat." See the following website: "Sacramento River: A Guide to Recreation and Public Access." Available at: *http://www.sacramentoriver.org/article.php?article_id=2*

caused by hydropower operations even while it is generating electricity, releasing water in a pattern much closer to reservoir inflows. The ability of a re-regulating dam to restore natural flow patterns will depend upon the extent to which the upstream hydropower dam has altered them; essentially the same volume of storage capacity is needed to both alter flows at the hydropower dam and to restore flows at the re-regulating dam. If hourly downstream fluctuations are undesirable, a relatively small re-regulating dam below the powerhouse can be a positive asset to hydropower and to the environment by providing a more steady downstream discharge during the day. However, if a large reservoir is being used to reshape the hydrograph over several months (for example, a season), that same large volume of water storage would be needed in the re-regulating reservoir to reshape the hydrograph back to a more natural pattern. The same benefit can be achieved by dedicating the lower-most hydropower dam in a cascade to re-regulate flows, which can be of considerable benefit to the downstream environment.

Other Design Considerations to Protect Downstream Ecosystems

While provision of adequate environmental flow releases will go a long way toward maintaining adequate habitat conditions and ecosystem services in rivers affected by dam development, other ecosystem protection measures will need to be addressed in an environmental impact assessment as well.

Sediment Bypasses and Sluice Gates

Sediment movement into and through a reservoir presents serious challenges for water storage. Sediment trapping in reservoirs seriously disrupts geomorphic processes that create high-value habitat below the reservoir, especially in watersheds with high sediment production rates. Sedimentation in a reservoir reduces the storage capacity available for hydropower generation, water supply, or other uses, and can create the risk of uncontrolled dam overtopping and collapse. Sediment accumulation in a reservoir is usually accounted for by providing *dead storage* in the bottom of a reservoir as an integral part of a dam project's design. Sediment moving through a reservoir and into hydropower intakes can severely damage turbines and shorten their lifespan.

Sediment trapping in a reservoir will usually have substantial impacts on downstream river channels and floodplains as well. If the water being released from the dam retains sufficient ability to erode the downstream river channel and banks, but sediment is not available from upstream to replace the eroded sediment, considerable channel down-cutting and instability can result, thereby endangering structures such as roads, bridges and levees and altering the physical habitats supporting aquatic life. The loss of sediment supply to downstream deltas and coastal areas can result in considerable erosion of beaches and islands of great importance for people and nature as well.

The implementation of sediment management measures—in the contributing watershed and in the reservoir—can greatly extend the design life of a dam and lead to other economic benefits, such as reducing the costs of maintaining hydropower turbines. Passing sediment around or through a dam can also help alleviate dam-related impacts in the downstream river ecosystem. The World Bank's publication entitled *Reservoir Conservation: The RESCON Approach* provides several highly useful approaches for managing sediment and evaluating the cost-effectiveness of sediment management measures. Some of the approaches discussed in that publication are summarized here.

In addition to providing dead storage to accommodate sediment deposition in a reservoir, new dam designs are including features to move sediment around or through the reservoir. These features are generally of two types. *Sediment bypass structures* are designed to route sediment inflows into a bypass outlet (a channel upstream of or in a reservoir that bypasses the dam and rejoins the river below the dam) and subsequently discharge sediment and water below the dam, thereby keeping sediment from flowing into hydropower turbines. *Sediment flushing* involves opening sediment sluice gates or other low-level outlets (usually located near the bottom of a dam; see Figure 3) and lowering reservoir levels to cause water in the reservoir to begin to flow through the reservoir and outlets. This flow needs to attain sufficient velocity to flush the sediments that have accumulated in the reservoir. This type of reservoir flushing entails a considerable tradeoff with power generation, however, because the reservoir level (head) must be lowered considerably, thereby compromising power generation potential during flushing. It can also complicate environmental flow management due to the fact that reservoir storage must be refilled following sediment flushing, reducing downstream flow releases during refill. Moreover, in large reservoirs, the sediment tends to deposit at the inflow end of the reservoir rather than behind the dam, limiting the ability to flush it through the sluice gates.

Figure 3. Sediment Sluice Gates in Three Gorges Dam, Yangtze River, China

Source: Three Gorges Dam: sluice gates. Retrieved June 12, 2007, from Encyclopedia Britannica Online at *http://www.britannica.com/eb/art-73592*.

When conducting an environmental flow assessment for a river reach below a dam, it is important to account for the changes in sediment transport caused by a dam. While high-flow releases from a dam may be necessary to accomplish some ecological purposes, they may also have unintended consequences by causing the bed and banks of the river channel to erode. Such erosion is a natural process in river ecosystems, but under natural conditions the eroded material is replaced by new material delivered from upstream. When a dam interrupts the upstream delivery of sediment, the net result may be erosion (down-cutting) of the river channel that is not refilled with new sediment. This can lead to many undesirable ecosystem consequences, such as changes in river depths and velocities and lowering of floodplain groundwater levels.

Fish Passage Structures

Structures such as “fish ladders” have commonly been used to enable fish and other mobile aquatic organisms to move upstream and downstream of a dam. However, the higher the dam wall, the harder and more expensive it is to build effective fish passages. Every dam, including those with fish passage structures, is likely to block the passage of some portion of the migratory fish. Each species will have particular design requirements for successful passage. For example, until recently, Australian dam builders constructed “horizontal baffle” fish ladders suitable for jumping salmonid fish—such as trout and salmon—imported from the Northern Hemisphere. However, most of Australia’s native fish do not jump and did not use these fish ladders, requiring instead “vertical slot” fish ladders that allow these species to rest in eddies at each step. Aquatic wildlife may migrate along riverbanks, requiring passages on each side of a barrier, or follow the “scent” of a strong water flow, requiring a strong current to flow from the wildlife passage to attract the animals to the entrance. Rock ramp fishways that mimic natural waterways may be the most effective wildlife passages, whereas at the other end of the spectrum, fish lifts and “catch and truck” operations are likely to assist only a modest portion of the migratory animals. Any dam without wildlife passage is likely to have a severe local impact on species diversity.

Key Points

- Many options and approaches are available for designing and operating new or existing hydropower dams, or cascades of dams, in a manner that minimizes or reduces their impacts on river ecosystems and associated ecosystem services.
- Tradeoff analyses can be used to assess various options for dam design and operation. While it is very challenging to bring together the requisite data and affected parties to conduct a comprehensive and objective tradeoff analysis, some best practices include: (a) stakeholder dialogue to identify valued components of ecosystems and processes; (b) assessment of environmental flows needed to protect ecosystem-related values; (c) engineering analysis of various dam options to meet ecosystem objectives, and the costs of necessary infrastructure and lost benefits such as hydropower generation; (d) compensation or mitigation for unavoidable impacts; and (e) adaptive management to verify delivery or protection of intended benefits.
- The collective values of stakeholders, political leaders, and dam managers for the outcome of dam development or management need to be expressed as a set of objectives that can be integrated explicitly into the dam development project. Such objectives should define both the environmental and social conditions that, when achieved, would constitute success.
- The characteristics of the flow regime necessary to meet ecosystem-related objectives (that is, environmental flow needs) need to be carefully considered in an environmental impact assessment. Regional estimates of environmental flow needs will need to be further refined as part of a local-scale environmental impact assessment. Many excellent methods and tools for site-specific evaluation of environmental flow needs have been developed in recent decades.
- The operating objectives for dam projects will likely change over time, in response to changing social priorities and climate change. This places a premium on flexibility to modify operations.
- Four dam design considerations that can provide considerable flexibility for meeting environmental flow needs at multi-objective dam projects are: (1) flood management in floodplains; (2) variable outlet and turbine-generator capacities; (3) multi-level, selective withdrawal outlet

structures; and (4) re-regulation reservoirs. Incorporating these physical features in the original construction of a dam will be far less costly than to retrofit them later.

- Other dam design features that can help protect river ecosystems include sediment bypasses or sluice gates, as well as fish passage structures.

VI. REVISITING EXISTING OPERATIONS

Few existing dams were designed with environmental flow releases to maintain downstream ecosystems, including floodplains, wetlands, deltas, and estuaries. However, recent technical investigations suggest that it is frequently possible to improve the environmental performance of existing dams without significantly reducing their social or economic benefits (Box 7). This work shows that such reoperation can also, in many instances, increase power generation, reduce downstream flood risks, and buffer the effects of climate change.

These benefits can be achieved by implementing various water or power management techniques that increase the flexibility of reservoir storage even while environmental flows are released into the downstream channel and floodplain. However, as many reoperation case studies have shown, the cost of adding new features to a hydropower dam scheme to better accommodate environmental flows or other enhancements—such as increasing the capacity of penstocks and turbines—can be quite expensive. It is usually far less expensive and difficult to incorporate environmental considerations in the design and construction of new dams than it is to retrofit them later.

Dams have been built for four main purposes in all regions of the world, although about 20 percent serve multiple functions. Among all purposes for dam construction, irrigation accounts for the largest proportion, followed by hydropower generation, flood control, and municipal water supply. The operating purpose(s) of a given dam dictates the operating plan and the extent to which the dam stores and releases water on a schedule that distorts natural flows. The purposes of the dam will therefore also determine the types of techniques that can be applied to create the operational flexibility that can enable environmental flows to be provided as a permanent operational feature.

As a general rule, investigating opportunities for modifying dam operations will require a thorough assessment of not only the operating rules that govern the day-to-day operations of any specific dam, but also the entire water management system for which the dam forms the water storage and power generation component. In cases where hydropower operations are primarily responsible for the flow alterations, an assessment of the potential for modifying the role that the hydropower dam plays in the entire mix of power generation stations feeding into the electrical grid will be essential. When the hydropower dam also operates for flood control or water supply, it is usually these other objectives that dictate the flow alteration pattern. It is these functions that will need to be reoperated to enable environmental flows to be generated. The techniques for doing so are also being developed, but are beyond the scope of this technical note.

The same design considerations described in sections IV and V will apply to reoperation of existing hydropower dam schemes. However, existing dams will pose some constraints, including the following:

- *Physical constraints posed by the dam infrastructure*. Most notably, the size of the outlet works and turbine-generator capacity may limit the rate at which water can be released from a dam, thereby precluding the release of controlled flood flows or making it infeasible to release water at low levels comparable to natural droughts.
- *Sediment trapping in reservoirs*. Dams interrupt the transport of sediments downstream, thereby modifying sediment transport processes downstream of the dam. This results in modified channel and floodplain habitats, to the detriment of native species and ecosystems.
- *Floodplain encroachment*. Floodplain encroachment by infrastructure (houses, roads) and various types of land uses such as high-value agriculture may limit the feasibility of controlled reintroduction of floods.

- *Higher-than-natural dam releases*. Higher-than-natural dam releases may be maintained during naturally low flow seasons or droughts to convey water for irrigation downstream; dilute wastewater discharges from factories, cities, and agricultural areas; or facilitate navigation. This poses more complex choices in restoring more natural low-flow conditions in the river ecosystem.

Restoring Natural Flow Patterns

In general, modifying operations of existing hydropower facilities to restore natural river flow characteristics involves moving their storage and release regime, as much as possible, in a direction that reduces daily and seasonal distortions in natural flows.

There are several approaches to achieving such reoperation. At the most basic level, operating regimes can be changed at individual facilities (*site level*). Where a cascade or complex of plants exists, more natural flows may be restored in the most ecologically significant reaches through compensatory adjustments in operations and flow regimes in other reaches, so that there is no net change in power production for the system as a whole (*cascade or complex level*). More fundamental shifts to natural regimes may mean moving dam operations in the direction of run-of-river operations, generating more electricity during high flow periods and less during low-flow periods, with compensatory adjustments at the grid system level (*system level)*.

The costs will vary among these approaches. Reoperation at site level is most likely to incur loss of generation or loss in peak generation revenue unless it is compensated for through regime changes, physical works (such as re-regulating reservoirs) or efficiency improvements in rehabilitation of civil and electro-mechanism components of a hydropower facility. At the cascade level, the costs and benefits may be redistributed among the several plants. Reoperation at the system level may preserve or even increase total annual generation at the facility (by maintaining reservoir levels at a higher average storage level and increasing capacity to generate power during high flow (and release) periods), but requires rescheduling generation at other (e.g., thermal) facilities. This may entail additional capital investments in the powerhouse, in transmission capacity and in powerplants used to fill in generation outside of high flow periods, or to ensure peak power and/or system stability.

These reoperation costs must be compared to the reoperation benefits (see Box 7), which may include:

- restored ecosystem benefits and associated improvements in livelihoods and food production systems;
- improvements in the quantity and reliability of hydropower generation;
- reduced risk of flood damage (because the floodplain is remanaged to accommodate higher environmental flow releases); and
- resilience against the hydrologic perturbations of global climate change.

In the context of a broader range of sustainable development values, choosing to manage hydropower facilities for the additional objective of environmental performance would reoptimize the system. At the new point of optimization, these higher costs of power generation may be offset or exceeded by the value of the ecosystem services that can be maintained or restored through environmental flow management.

Environmental flow restoration can be implemented to varying degrees to achieve a new optimization point, taking all relevant economic and environmental values into account. A thorough environmental flow assessment that identifies the ecological benefits associated with each increment of environmental flow restoration should guide this tradeoff analysis.

Box 7. Restoring Flooding on the Waza-Logone Floodplains, Cameroon

The Waza-Logone floodplain covers approximately 8,000 square kilometers in northern Cameroon. The floodplains are formed by the confluence of the Chari and Logone rivers, which contribute approximately 95 percent of Lake Chad's inflows. The ecological and economic integrity of the Chari-Logone basin is dependent on the annual flooding (which normally extends from August to December in wet years) of the floodplain wetlands. Agriculture, fishing, pastoralism, and harvesting of forest products are important activities supported by the Waza-Logone floodplain. They are also important for biodiversity. In addition, the floodplains contain the Waza National Park and the Kalamahoue National Park.

The completion of the Maga Dam in 1981 to support irrigated rice cultivation, in conjunction with prolonged periods of poor rainfall and the overharvesting of natural resources, reduced the flood extent of the Waza-Logone floodplains by approximately 1,000 to 2,000 km². This resulted in a decline in wildlife and biodiversity, collapse of the fishing industry, reduced grazing capacity, and a shortage of surface water in the dry season. In order to survive, the different user groups in the basin were forced to diversify into activities previously practiced by the other groups. Consequently, the number of conflicts between the different users of the floodplain increased.

In a collaborative effort between the Institute of Environmental Sciences (CML) of Leiden University in the Netherlands and IUCN, the first pilot release of water into the floodplain occurred in 1994 and a second in 1997. According to the project, the "combined channel flows…resulted in an annual increase in the area flooded in an average year of around 200 km²."

The reflooding of the pilot zone in the Waza-Logone floodplain had both ecological and economic benefits. The rangelands improved as the vegetation recovered from annual grass species back to perennial species; as a result, livestock were in better condition and pastoralists spent more time in the pilot zone. The project found that the increase in flooded area also provided additional habitat for water birds and fish. IUCN calculated that fishers caught 1,777 tons of fish in the additional 200 km² of flooded area. In addition, traditional crops such as floating rice and flood-fed sorghum were able to be cultivated in the floodplain again. The increase in environmental benefits correlated to increased economic benefits, particularly for pastoralists who experienced higher incomes from improved sales of milk and livestock. A noneconomic benefit of the reflooding was improved relations in the way the ethnic groups shared the floodplain.

For more information:

IUCN. 2000. Rapport final phase III du projet Waza Logone, UICN - Union mondiale pour la nature, Projet de Conservation et de Développement de la Région de Waza-Logone, Maroua.

Loth, Paul, ed. 2004. *The Return of the water: Restoring the Waza Logone floodplain in Cameroon*. Gland, Switzerland: IUCN Wetlands and Water Resources Programme.

MacDonald, M. 1993. *Mathematic Model of the Hydrological Behaviour of Lake Chad and Its Feeder Rivers*. Main Report to the United Nations Department for Technical Cooperation for Development, UNDP and LCBC. Cambridge, UK: Mott MacDonald.

MacDonald, M. 1999. "Logone Floodplain Model Study Report." Cambridge, UK: Mott MacDonald.

Waza-Logone Pilot Project Website: *http://www.lakechadbasin.net*

Selecting Best Candidates for Dam Reoperation

Developing a practical reoperation plan for hydropower facilities requires a considerable investment in data gathering, operational modeling, and economic analysis. Before such investments are warranted, it is useful to identify dams that—at least superficially—appear to be the best prospects for beneficial reoperation. A screening tool can be very useful when applied with basic information and criteria.

The flow chart in Figure 4 is such a tool. It is a purposefully oversimplified screening device, designed to identify only the most promising candidates for reoperation, not all the candidates that a more detailed analysis might reveal to be practical targets. This tool focuses on the physical requisites for the successful application of a suite of improved water and power management techniques. It does not consider the economic or legal/institutional/political requisites or constraints that will also be important. These considerations are most efficiently applied to those dams that survive the technical feasibility screen. It also does not attempt to determine whether ecosystem restoration objectives can be met through the implementation of these operational changes. That is left to a further stage of analysis. Basically, the screening tool identifies the characteristics that would likely qualify or disqualify a dam for beneficial reoperation. A large middle category will be left with indeterminate results. This is intentional, as efficiency of analysis is more desirable than comprehensiveness at this stage of screening.

Figure 4. Screening Tool for Selecting Best Candidates for Dam Reoperation[1]

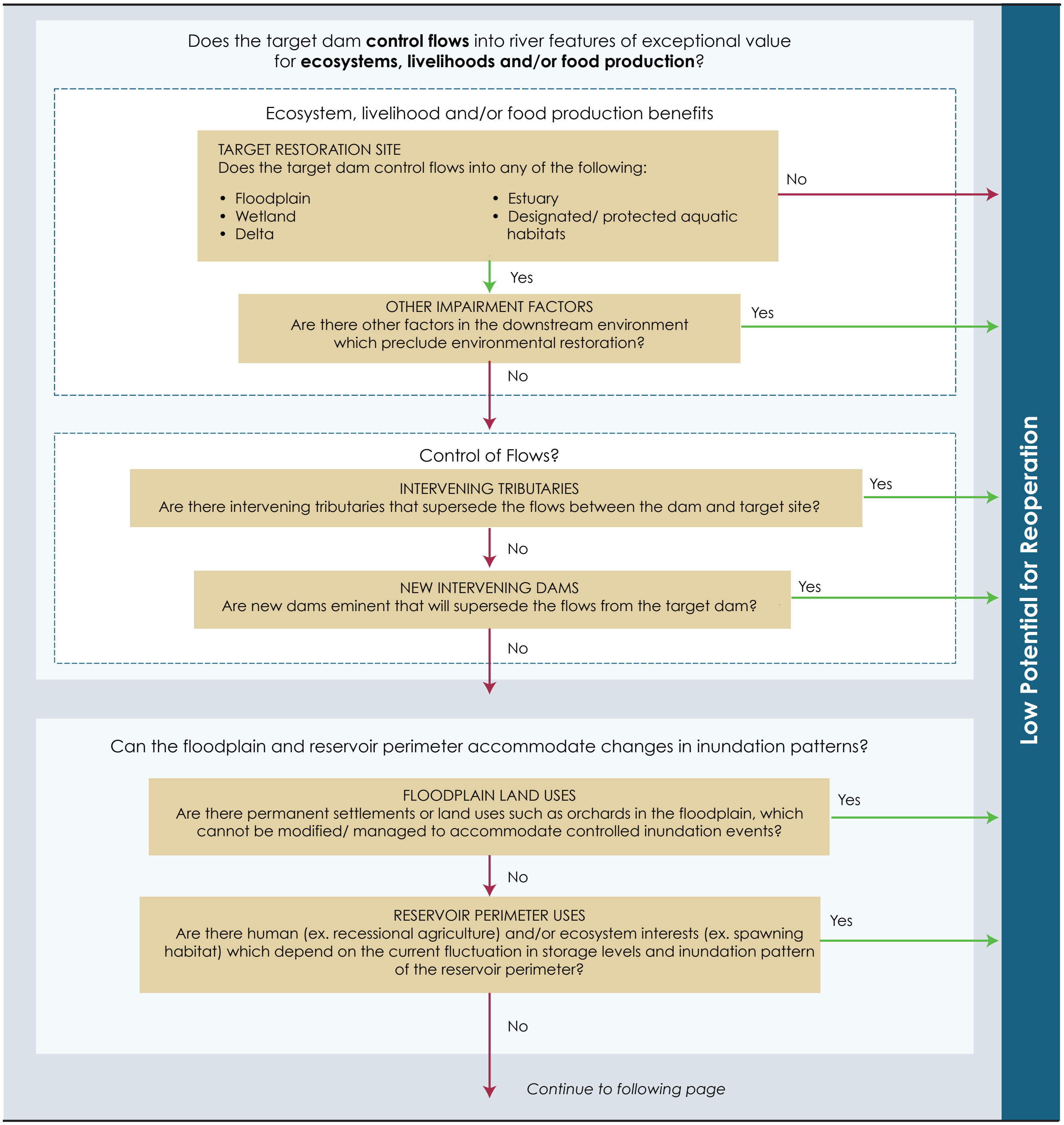
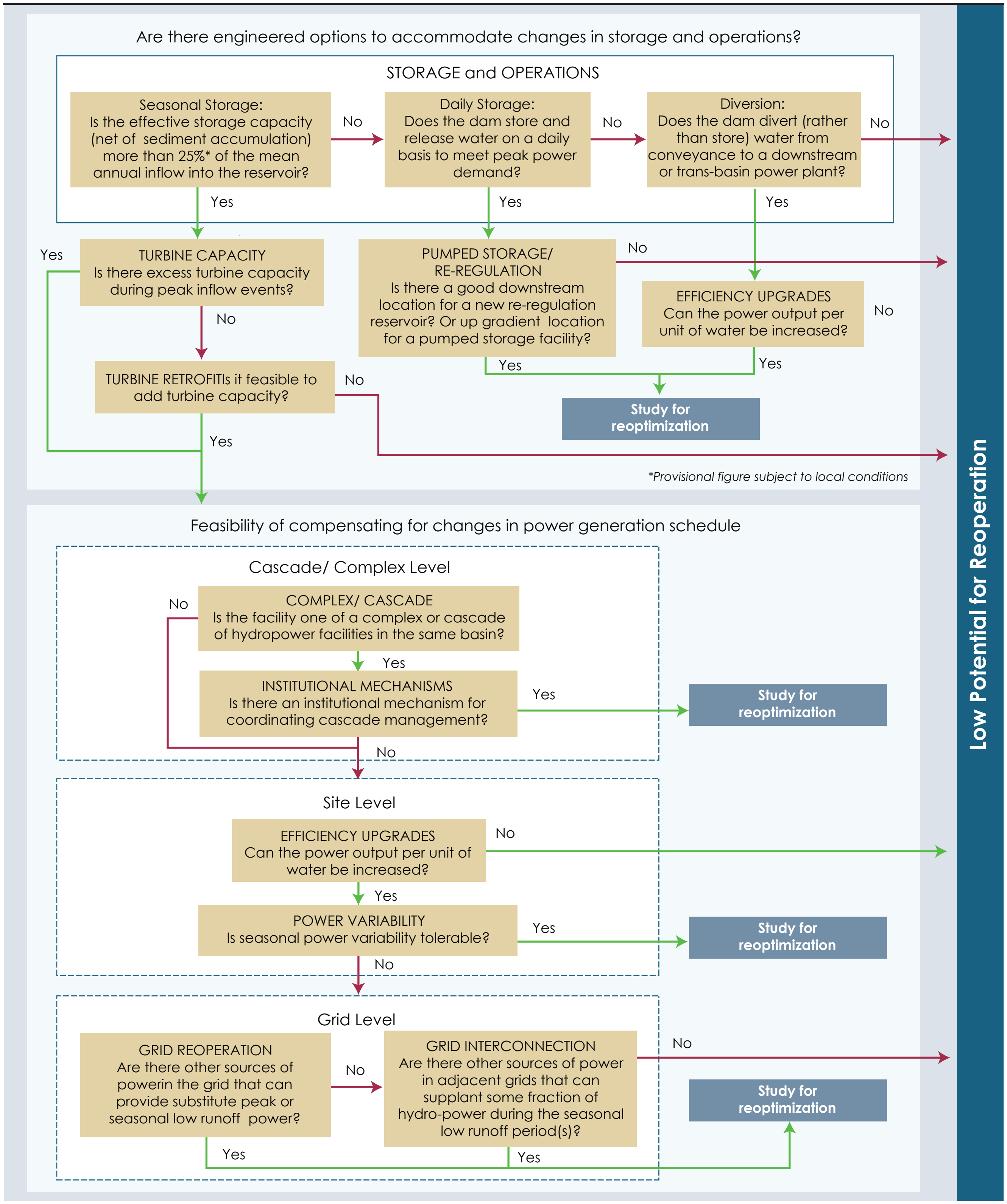


Figure 4. Screening Tool for Selecting Best Candidates for Dam Reoperation[1] *(cont.)*



[1] *Source:* Natural Heritage Institute & The Nature Conservancy (2008). Guidance from the Natural Heritage Institute on use of this tool can be found at www.global-dam-re-operation.org/resources/tools-databases.html

Key Points

- Many recent experiences suggest that it is frequently possible to improve the environmental performance of existing dams (called *reoperation*) with little to no social or economic disruption. In fact, in many cases an assessment of the feasibility of dam reoperation can identify ways to create multiple benefits.
- Reoperation can be accomplished by implementing various water or power management techniques that increase the flexibility of reservoir storage and releases such that environmental flows can be released into the downstream channel and floodplain.
- Most reoperation projects involve restoring key characteristics of natural flow regimes that support critical ecosystem functions.
- As a general rule, investigating opportunities for modifying dam operations will require a thorough assessment of not only the operating rules that govern the day-to-day operations of any specific dam, but also the entire water management system for which the dam forms the water storage and power generation component.
- Common constraints on reoperating dams include physical limitations of the dam's design, potential for increased channel instability downstream, floodplain encroachment below the dam, and the need to provide higher-than-natural flows to dilute wastewater discharges or facilitate navigation.
- Flow restoration efforts (not all involve hydropower dams) are now under way in more than 850 river basins in more than 50 countries.

VII. THE ROLE OF ADAPTIVE MANAGEMENT

In the siting, design, operation, and reoperation of hydropower dams, questions will arise about likely short- and long-term ecosystem impacts. While the best available expert knowledge and analysis should be employed in every step, dam developers, governments, and stakeholders need to understand that the environmental consequences of dam development and operations cannot be predicted with complete certainty. To be ecologically sustainable, water development and management need to be perpetually informed by monitoring, carefully targeted data collection and research, and further analysis to address new uncertainties or surprises. Therefore, a program of monitoring, evaluation, and adjustment—commonly referred to as *adaptive management*—should be fully and explicitly integrated into any hydropower development or reoperation plan so that management approaches can be continually modified in light of increased understanding or changes in human and ecosystem conditions. The economic risks associated with uncertain environmental constraints need to be addressed explicitly as part of the adaptive management strategy.

Monitoring Program

Attaining ecosystem-related objectives will usually require environmental flow releases from dams. However, the scientific process of determining environmental flow needs is fraught with uncertainties about the likely response of plants, animals, and ecological processes to hydrologic changes caused by dam operations. It is therefore very important for scientists that are involved in hydropower projects to formulate a set of testable hypotheses during the development of an environmental flow prescription that can be rigorously examined during dam operations.

These hypotheses should focus on both short- and long-term responses. For example, over the long term, it might be hypothesized that the prescribed environmental flow regime will enable the population of a target fish species to fluctuate within a specified range. But the testing of this hypothesis may take many years before long-term fluctuations are well understood. Therefore, it might also be beneficial to develop and test other hypotheses that can inform dam operations in a shorter term, such as postulating that a specified flow will enable the fish species to access its spawning area on the floodplain at the appropriate time of the year. The Savannah River case study presented in Box 5 and Figure 2 focuses on both short- and long-term ecological outcomes. Each of the ecological responses to environmental flow releases illustrated in Figure 2 can be viewed as a hypothesis that can be tested by experimental or pilot dam releases. By evaluating the results of such testing, a great deal of knowledge about flow-ecology relationships can be gained in short order.

It is important to test these hypotheses as new dams are being built, or as existing dams are reoperated for environmental benefits. This testing can be accomplished by designing an ecosystem-monitoring program during the development of an environmental impact assessment (Box 8). The monitoring program should begin implementation prior to dam construction or reoperation, so that baseline conditions can be documented. Monitoring should continue as new or modified dam operations are being implemented. By establishing the baseline conditions prior to the new project, the dam-induced changes in the ecosystem can be better understood.

Box 8. Adaptive Management of Hydropower Operations: Roanoke River, North Carolina, U.S.

The lower Roanoke River in North Carolina has been regulated by a series of dams since the 1950s. The river and floodplain downstream of these dams support plants and animals that are highly valued for fishing and hunting, timber production, and wildlife viewing. The bottomland hardwood forest found along the lower Roanoke is one of the most extensive and least fragmented in the eastern U.S.A., providing habitat for a long list of imperiled plant and animal species. However, upstream dam operations have been causing unnaturally long floods during the growing season, threatening the survival of the forest and its extraordinary habitat value.

A relicensing process for private hydropower dams, administered by the Federal Energy Regulatory Commission (FERC), provided the stimulus for examining the Roanoke dam operations and their ecological impacts. A coalition of stakeholders, including public wildlife agencies and private conservation organizations, collaborated with the owner of the two lowermost dams on the river to develop an adaptive management program to alleviate the ecological impacts attributed to dam operations.

The adaptive management program is designed to test the hypothesis that within-week peaking strategies being employed by the dam operator are causing extended growing season inundation that impairs the regeneration of the bottomland hardwood forest. This hypothesis was formulated after developing a reservoir operations and flood routing model, calibrated with considerable field data, which provided insights into the effects of hydropower operations on downstream flows and floodplain inundation. This hypothesis is being tested by measuring inundation levels and frequencies along with tree seed germination and seedling mortality, focusing on 12 tree species. To supplement this monitoring effort, data is being gathered on other plants and animals also believed to be vulnerable to long-duration flooding.

The specific objectives of the adaptive management program were formalized as part of a FERC relicensing agreement in 2003. This agreement calls for the dam operator to reduce growing season inundation of the floodplain to the point of insignificance for the bottomland hardwood tree species, as measured by agreed-upon biological indicators such as tree seedlings surviving at the targeted rate. To provide some certainty for the dam operator and to provide a sufficiently slow transition in dam operations to allow the operator to secure or use other generating sources to make up any lost power, the settlement agreement calls for reoperation to be undertaken in five-year increments. During each five-year period, the dam operator is required to reduce its unnatural flooding impacts (as measured by a flood index) by half, until ecological effects become undetectable. Modeling simulations suggest that at a maximum, power production will be reduced by less than three percent per year.

For More Information:

Pearsall, S.H., B.J. McCrodden, and P.A. Townsend. 2005. "Adaptive management of flows in the Lower Roanoke River, North Carolina, USA." *Environmental Management* 35: 1–15.

Adaptability in Dam Operations

The social, economic, and environmental objectives for dam management should be developed with stakeholders. The formulation of mutually desirable objectives related to ecosystem health, economic benefits, and other societal needs and preferences should be an explicit product of regional- and local-scale planning. Dam management activities can then be directed at trying to fully attain these objectives. This may require numerous iterations or trials, such as making modifications to dam operating rules or energy production cycles. These adjustments can be informed by experimental testing of flow-ecology relationships, as mentioned previously. It may also become necessary to revisit mutually agreed-upon objectives if it becomes apparent that the full suite of objectives cannot be realistically attained.

Unfortunately, traditional water management plans have commonly been formulated in ways that make them difficult, if not impossible, to modify frequently or quickly. For example, specific requirements for provision of environmental flows below private hydropower dams in the United States are commonly specified in 30-to-50-year dam operating licenses, making modifications to these flow requirements costly, time-consuming, or legally problematic. Additionally, the design of water infrastructure, such as water release structures or turbines at dams, or pipes and pumps used to divert water from a river, can place serious constraints on management flexibility if these structures are not designed to pass variable volumes of water to meet environmental flow needs.

Sustainable energy or water management plans should preserve the ability to respond to new information gained from a monitoring program, and to alter the plan and related infrastructure operations accordingly. This ultimately depends on the flexibility of water management infrastructure, regulatory or legal mechanisms controlling water use, and the political will to stay with an ever-evolving process. Over the long term, managing adaptively to meet the goal of sustainable energy or water management will increase certainty as the most troublesome uncertainties are resolved, infrastructure operations are refined for greater efficiency and compatibility, and ecological degradation halted. As adjustments in the status quo are required, parties may need to seriously explore ways to share and minimize the financial and economic impacts, including the possibility of indemnification agreements that cover some of the costs associated with these changes. If it is impossible to implement new or modified water management strategies over time, the options for attaining sustainable management will be diminished greatly.

Dam Decommissioning

It is inevitable that dams will eventually need to be decommissioned as society's needs change or the structures become old and unsafe. An adaptive management strategy should make provision for decommissioning. This may include structural provisions in the dam design and economic trusts that will pay for decommissioning.

Governance

Managers of hydropower dam schemes will need to continually respond to new ecological information and social needs by modifying their operations plan. The process and authorities for such decision-making should be clearly articulated in the operational plan. Ideally, this governance includes the formation of a peer review committee, chartered with responsibility for reviewing the results of ecological monitoring and making recommendations to a river basin commission or other local or regional management or regulatory agency with ultimate decision-making authority. At the same time, the uncertainty in costs and revenues commonly perceived for adaptive management must be addressed and risks appropriately allocated across the hydropower developer and other players, including public institutions.

Secure Funding

The management plan should also identify funding needs and sources, with an emphasis on sources that can provide for long-term security. Even short-term breaks in funding support can severely impact water management and monitoring programs. The success of ecological monitoring programs relies upon continuous, consistent measurements adequate to capture short-term and inter-annual fluctuations in flow and ecosystem conditions. Tying funding sources to reliable revenues such as hydropower revenues may provide greater dependability.

Key Points

- The environmental consequences of dam development and operations cannot be predicted with complete certainty. Therefore, it is essential that a program of monitoring, evaluation, and adjustment—commonly referred to as *adaptive management*—be fully and explicitly integrated into both regional and local plans.
- The assumed response of the river ecosystem to a new dam, or an existing dam to be reoperated, should be formulated as scientific hypotheses that can be tested through implementation of a monitoring program.

- The monitoring program should be implemented prior to dam construction or reoperation, so that baseline conditions can be documented. Monitoring should continue as new or modified dam operations are being implemented.
- The feasibility of adaptive management will often depend on dam design features that facilitate flexibility in dam operations.
- Successful adaptive management requires active governance and adequate funding.

ANNEX 1. RECOMMENDED READING

General Reading

Grey, D. and C. Sadoff. 2005. *Water for Growth and Development: A Framework for Analysis.* Baseline Document for the 4th World Water Forum, Theme 1: Water for Growth and Development. Available at: http://www.worldwaterforum4.org.mx/uploads/TBL_DOCS_46_55.pdf

International Hydropower Association. 2004. *Sustainability Guidelines*. Available at: http://www.hydropower.org/downloads/IHA%20Sustainability%20Guidelines_Feb04.pdf

Ledec, G. and J.D. Quintero. 2003. *Good Dams and Bad Dams: Environmental Criteria for Site Selection of Hydroelectric Projects.* Latin America and Caribbean Region Sustainable Development Working Paper 16. Washington, DC: The World Bank, Latin America and Caribbean Region, Environmentally and Socially Sustainable Development Department.

Mallon, K., G. Bourne, and R. Mott. 2007. *Climate Solutions: WWF's Vision for 2050*. Gland, Switzerland: WWF International.

Scudder, T. 2005. *The Future of Large Dams: Dealing with social, environmental, institutional and political costs.* London: Earthscan.

Silk, Nicole, and Kristine Ciruna, eds. 2004. *A Practitioner's Guide to Freshwater Biodiversity Conservation*. Arlington, VA: The Nature Conservancy. Reprint edition published by Island Press (2005).

World Commission on Dams. 2000. *Dams and Development: A New Framework for Decision-Making.* London and Sterling, VA: Earthscan Publications Ltd.

Further Technical Information

Adaptive Management

National Research Council. 2004. *Adaptive Management for Water Resources Project Planning*. Panel on Adaptive Management for Resource Stewardship, Committee to Assess the U.S. Army Corps of Engineers Methods of Analysis and Peer Review for Water Resources Project Planning. Washington, DC: National Academy of Sciences.

Pearsall, S., B. McCrodden, and P. Townsend. 2005. "Adaptive Management of Flows in the Lower Roanoke River, North Carolina, USA." *Environmental Management* 35 (4): 353–367.

Rogers, K.H., and R. Bestbier. 1997. *Development of a protocol for the definition of the desired state of riverine systems in South Africa.* Pretoria, South Africa: Department of Environmental Affairs and Tourism.

Ecological Impacts of Altered Flows and Dams

Bunn, S.E., and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30 (1): 492–507.

Collier, M., R. Webb, and J. Schmidt.1996. *Dams and rivers: A primer on the downstream effects of dams*. U.S. Geological Survey Circular 1126. Reston, VA: U.S. Geological Survey.

Friedman, J.M., W.W. Osterkamp, M.L. Scott, and G.T. Auble. 1998. "Downstream Effects of Dams on Channel Geometry and Bottomland Vegetation: Regional Patterns in the Great Plains." *Wetlands* 18:619–633.

Ligon, F., W. Dietrich, and W. Trush. 1995. "Downstream Ecological Effects of Dams." *BioScience* 45 (3): 183–192.

McCully, P. 1996. *Silenced Rivers: The Ecology and Politics of Large Dams*. London: Zed Books.

Morse, B. and T. Berger. 1992. *Sardar Sarovar - Report of the Independent Review*. Ottawa: The World Bank, Resource Futures International.

Ward, J.V. and J.A. Stanford. 1983. "The serial discontinuity concept of lotic ecosystems." In T.D. Fontaine III and S.M. Bartell, eds. *Dynamics of Lotic Ecosystems*. Ann Arbor, MI: Ann Arbor Science.

Williams, G.P. and M.G. Wolman. 1984. *Downstream Effects of Dams on Alluvial Rivers.* USGS Professional Paper 1286. Washington, DC: US Government Printing Office.

Environmental Flow Assessment and Implementation

Davis, R. and R. Hirji, R., eds. 2003. *Environmental Flows: Concepts & Methods*. Water Resources and Environment Technical Note C.1. Washington, DC: The World Bank.

Davis, R. and R. Hirji, eds. 2003. *Environmental Flows: Case Studies*. Water Resources and Environment Technical Note C.2. Washington, DC: The World Bank.

Davis, R. and R. Hirji, eds. 2003. *Environmental Flows: Flood Issues*. Water Resources and Environment Technical Note C.3. Washington, DC: The World Bank.

Dyson, M., G. Bergkamp, and J. Scanlon, eds. 2003. *Flow: the Essentials of Environmental Flows.* Gland, Switzerland: IUCN.

Hirji, R. and R. Davis, eds. 2009. *Environmental Flows in Water Resources Policies, Plans, and Projects: Findings and Recommendations*. Washington, DC: The World Bank.

Hirji, R. and R. Davis, eds. 2009. *Environmental Flows in Water Resources Policies, Plans, and Projects: Case Studies*. Washington, DC: The World Bank.

Olsen, S. B., R.V. Padma, and B.D. Richter. 2006. *A Guide to Managing Freshwater Inflows to Estuaries.* Providence, RI: University of Rhode Island, Coastal Resource Center.

Poff N. L., Richter B. D., Arthington A. H., Bunn S. E., Naiman R. J., Kendy E., Acreman M., Apse C., Bledsoe B. P., Freeman M. C., Henriksen J., Jacobson R. B., Kennen J. G., Merritt D. M., O'Keefe J. H., Olden J. D., Rogers K., Tharme R. E. & Warner A. (2009) The Ecological Limits of Hydrologic Alteration (ELOHA): A new framework for developing regional environmental flow standards. Freshwater Biology Published Online Sep 2 2009, DOI: 10.1111/j.1365-2427.2009.02204.x. http://rydberg.biology.colostate.edu/~poff/PoffPublicationsPDF.htm

Poff N. L., Richter B. D., Arthington A. H., Bunn S. E., Naiman R. J., Kendy E., Acreman M., Apse C., Bledsoe B. P., Freeman M. C., Henriksen J., Jacobson R. B., Kennen J. G., Merritt D. M., O'Keefe J. H., Olden J. D., Rogers K., Tharme R. E. & Warner A. (2009) The Ecological Limits of Hydrologic Alteration (ELOHA): A new framework for developing regional environmental flow standards. *Freshwater Biology* Published Online Sep 2 2009, DOI: 10.1111/j.1365-2427.2009.02204.x. http://rydberg.biology.colostate.edu/~poff/PoffPublicationsPDF.htm

Postel, Sandra and Brian Richter. 2003. *Rivers for Life: Managing Water for People and Nature*. Washington, DC: Island Press.

Richter, B.D., A.T. Warner, J.L. Meyer, and K. Lutz. 2006. "A collaborative and adaptive process for developing environmental flow recommendations." *River Research and Applications* 22: 297–318.

Richter, B.D., J. Baumgartner, R. Wigington, and D. Braun. 1997. "How much water does a river need?" *Freshwater Biology* 37 (1): 231–249.

Richter, B. D., R. Mathews, D.L. Harrison, and R. Wigington. 2003. "Ecologically sustainable water management: managing river flows for ecological integrity." *Ecological Applications* 13: 206–224.

The Nature Conservancy. *Flow Restoration Database*. Available at: www.nature.org/initiatives/freshwater/conservationtools

Modifying Dam Designs and Operations for Environmental Benefits

Blanch, S., ed. 2001. *The way forward on weirs.* Sydney, Australia: Inland Rivers Network.

Richter, Brian D., and Gregory A. Thomas. 2007. Restoring Environmental Flows by Modifying Dam Operations. *Ecology and Society* 12 (1): 12. Available at: *http://www.ecologyandsociety.org/vol12/iss1/art12/*

Regional Planning for Biodiversity and Ecosystem Services

Abell R., J.D. Allen, and B. Lehner. 2007. "Unlocking the potential of protected areas for freshwaters." *Biological Conservation* 134: 48–63.

Harrison, D., J. Opperman, and B. Richter. 2007. "Can Hydropower Be Sustainable?" *International Water Power and Dam Construction* 59: 22–25.

Higgins, J. V. 2003. "Maintaining the ebbs and flows of the landscape—conservation planning for freshwater ecosystems." In C. R. Groves, ed. *Drafting a conservation blueprint: a practitioner's guide to regional planning for biodiversity*. Washington, DC: Island Press.

Higgins, J., M. Bryer, M. Khoury, and T. Fitzhugh. 2005 "A Freshwater Classification Approach for Biodiversity Conservation Planning." *Conservation Biology* 19 (2): 432–445.

Niasse, M., A. Afouda, and A. Amani, eds. 2004. *Reducing West Africa's Vulnerability to Climate Impacts on Water Resources, Wetlands and Desertification: Elements for a Regional Strategy Preparedness and Adaptation.* Gland, Switzerland and Cambridge, UK: IUCN.

Omernick, J.M., and R.G. Bailey. 1997. "Distinguishing between watersheds and ecoregions." *Journal of the American Water Resources Association* 33: 935–949.

Sullivan, M., and R.A. Giffen. 1985. *The Maine Rivers Policy*. Paper presented at the Symposium on Small Hydropower and Fisheries, Denver, Colorado, May 1–3, 1985.

The World Bank. 2003. *Stakeholder Involvement in Options Assessment: Promoting Dialogue in Meeting Water and Energy Needs*. Washington, DC: World Bank.

Sediment Management

Kawashima, S. et. al. 2003. *Reservoir Conservation: The RESCON Approach*. Volume I. Washington, DC: World Bank.

Kawashima, S. et. al. 2003. *Reservoir Conservation: RESCON Model and User Manual*. Volume II. Washington, DC: World Bank.

Tradeoff Analysis and Ecosystem Service Valuation

Emerton, Lucy. 1994. *An Economic Valuation of the Costs and Benefits in the Lower Tana Catchment Resulting from Dam Construction*. Report prepared by Acropolis Kenya Ltd. for Nippon Koei, Nairobi.

Emerton, L. and E. Bos. 2004. *Value: Counting Ecosystems as an Economic Part of Water*. Gland, Switzerland: IUCN.

Jager, Henriette I., and Mark S. Bevelhimer. 2007. "How Run-of-River Operation Affects Hydropower Generation and Value." *Environmental Management*. 40:1004–1015.

Kotchen, Matthew J., et. al. 2006. "Environmental Constraints on Hydropower: An Ex Post Benefit-Cost Analysis of Dam Relicensing in Michigan." *Land Economics*. 82 (3): 384–403.

Krchnak, Karin M., et. al. 2007. *Watershed Valuation as a Tool for Biodiversity Conservation: Lessons Learned from Conservancy Projects*. Arlington, VA: The Nature Conservancy.

McCartney, Matthew P. 2007. *Decision Support Systems for Large Dam Planning and Operation in Africa.* Working Paper 119. Colombo, Sri Lanka: International Water Management Institute.

Millennium Ecosystem Assessment 2005. *Ecosystems and Human Well-being: Synthesis*. Washington, DC: Island Press.

Wong, C.M., C.E. Williams, J. Pittock, U. Collier, and P. Schelle. 2007. *World's Top 10 Rivers at Risk*. Gland, Switzerland: WWF International.

WWF Global Freshwater Programme. 2006. *Free-Flowing Rivers: Economic Luxury or Ecological Necessity?* Zeist, Netherlands: WWF.