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Research

Overcoming Information Limitations for the Prescription of an Environmental Flow Regime for a Central American River

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ABSTRACT. Hydropower dam construction is expanding rapidly in Central America because of the increasing demand for electricity. Although hydropower can provide a low-carbon source of energy, dams can also degrade socially valued riverine and riparian ecosystems and the services they provide. Such degradation can be partially mitigated by the release of environmental flows below dams. However, environmental flows have been applied infrequently to dams in Central America, partly because of the lack of information on the ecological, social, and economic aspects of rivers. This paper presents a case study of how resource and information limitations were addressed in the development of environmental flow recommendations for the Patuca River in Honduras below a proposed hydroelectric dam. To develop flow recommendations, we applied a multistep process that included hydrological analysis and modeling, the collection of traditional ecological knowledge (TEK) during field trips, expert consultation, and environmental flow workshops for scientists, water managers, and community members. The final environmental flow recommendation specifies flow ranges for different components of river hydrology, including low flows for each month, high-flow pulses, and floods, in dry, normal, and wet years. The TEK collected from local and indigenous riverine communities was particularly important for forming hypotheses about flow-dependent ecological and social factors that may be vulnerable to disruption from dam-modified river flows. We show that our recommended environmental flows would have a minimal impact on the dam's potential to generate electricity. In light of rapid hydropower development in Central America, we suggest that environmental flows are important at the local scale, but that an integrated landscape perspective is ultimately needed to pursue hydropower development in a manner that is as ecologically sustainable as possible.

Key Words: *dams; environmental flows; fish assemblage; Honduras; hydrology; traditional ecological knowledge; tropics*

INTRODUCTION

Construction of dams for power generation is expanding rapidly in Central America because of high population growth, rural electrification efforts, and increased demand for electricity (Scatena 2004). Electricity consumption throughout the region is increasing 5%–9% each year (Comisión Económica para América Latina y el Caribe (CEPAL) 2006). Hydropower is a preferred generation method in Central America because the primary resources, water and topographical gradient, are in high supply and because it is a proven solution to national energy needs—approximately 50% of the electricity in Central America was generated by hydropower dams in 2005 (Energy Information Administration (EIA) 2010). Costa Rica alone built more than 30 new hydroelectric plants during the 1990s (Braga et al. 2000, Anderson et al. 2006). A recent assessment of future hydroelectric development anticipates an expansion in hydropower capacity in Central America, with 370 planned hydropower dam sites with a potential aggregate installed capacity of 16 165 MW (Burgués-Arrea 2005).

Because dams can cause substantial social and environmental impacts (World Commission on Dams 2000), proposed hydropower expansion on the scale contemplated in Central America raises important questions about sustainability. Although much attention has focused on the human

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communities and habitats displaced by reservoirs, dams can also significantly affect downstream habitats and livelihoods by altering a river system's natural flow, sediment, and energy regimes (Baron et al. 2002, Postel and Richter 2003, Fitzhugh and Richter 2004). River flow can be considered a "master variable" that controls many of the fundamental physical, energetic, and biological characteristics of a river system and its floodplain (Poff et al. 1997). Disruption of the natural flow regime can therefore disrupt entire river ecosystems and the socioeconomic activities that depend on them (Sparks 1995, Walker et al. 1995, Poff et al. 1997, Baron et al. 2002, Postel and Richter 2003). In part because of altered natural flow regimes, species in freshwater ecosystems are endangered at rates far higher than those in terrestrial and marine ecosystems (Richter et al. 1997, Ricciardi and Rasmussen 1999). Dam-induced alterations to river flow can also degrade or change many of the benefits that humans derive from these ecosystems. This is particularly true in developing countries where millions of people rely directly on flow-influenced ecosystems—rivers, floodplain forests, riparian wetlands, and nearshore marine ecosystems—for their basic subsistence needs (Postel and Richter 2003).

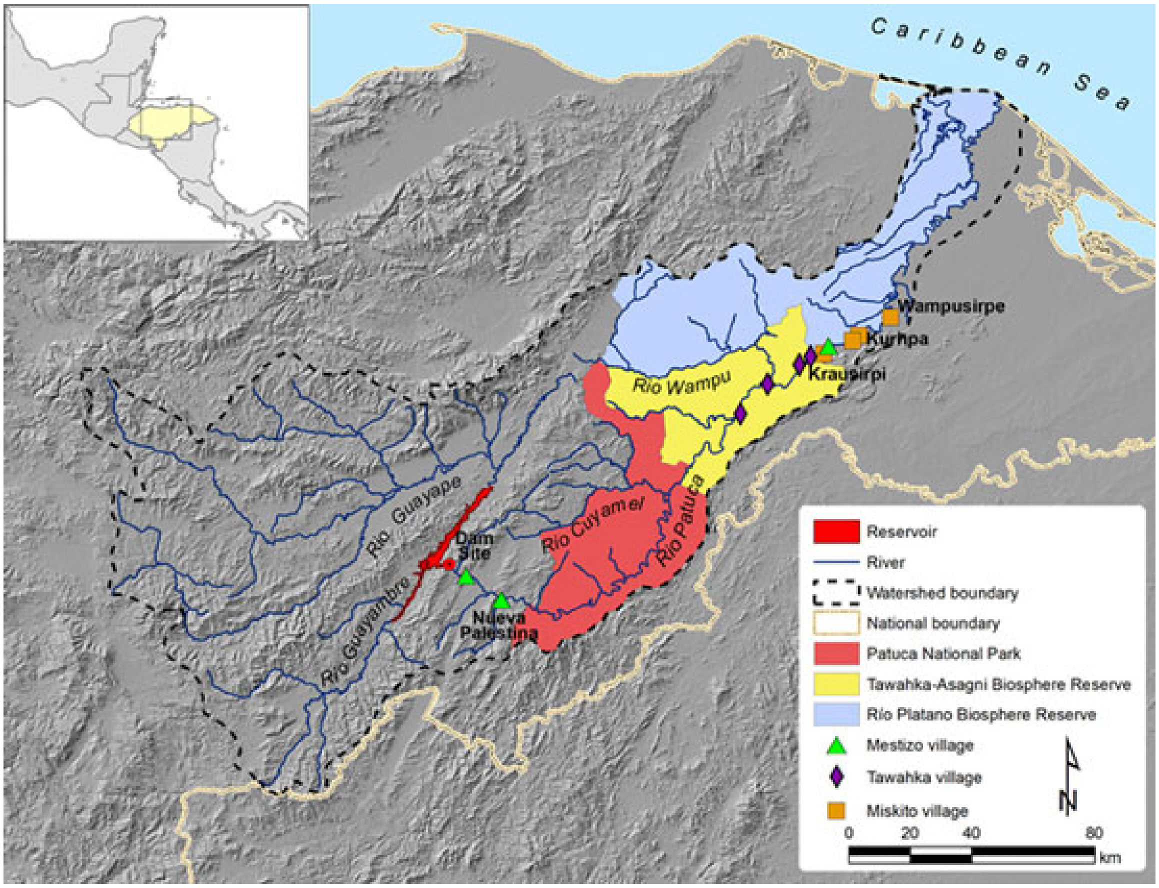
Although many definitions of sustainability have been offered, most efforts to describe sustainable hydropower emphasize that hydropower benefits should be balanced with the ecological and social values of a river system, and that environmental and social impacts must be avoided, minimized, or mitigated at all stages of the development process (International Hydropower Association 2006). Because most riverine resources and values depend on the flow regime, this suggests that sustainable hydropower must strive to protect the aspects of a river's flow that are important to society and ecosystems (Bratrich et al. 2004). Such flows—often called "environmental flows"—have been the focus of much research around the world. The vast majority of environmental flow projects and studies have been conducted in North America, Europe, and Australia, countries with relatively high levels of financial resources and relevant scientific and other expertise. Fewer efforts have been made to develop environmental flow recommendations for countries in the developing world (Tharme 2003), where information and logistical challenges commonly differ from those in economically well-developed countries.

In Central America, budgets are small or non-existent for physical or biological data collection, and comparatively few scientists are available to conduct in-country research (Pringle et al. 2000). As a result, data available for developing environmental flow recommendations are scarce or completely lacking for most rivers, and financial constraints greatly limit research and modeling efforts. Thus, developing environmental flow recommendations for the region's rivers will require technically defensible methods that do not rely heavily on empirical data. Richter et al. (2006) described a process—now referred to as the "Savannah Process" for the river in which it was first applied—in which environmental flow recommendations can be developed in an interdisciplinary workshop setting with expert input. This approach integrates whatever information is available, along with expert judgment into a framework that can be adapted to the level of information and funding available. In this paper, we present a case study of how we adapted the Savannah Process to develop environmental flow recommendations for a Central American river, the Patuca River in Honduras, for which little scientific data and few experts were available.

The Patuca River encapsulates many of the logistical, environmental, and social challenges of developing environmental flow recommendations in Central America. The Patuca is the third longest river in Central America and supports important aquatic biodiversity and an array of estuarine and nearshore ecosystems. The Honduran government has approved the development of a hydroelectric dam, known as Patuca 3, for the currently unregulated river. Below the proposed dam, the Patuca River flows through three national protected areas that include the roadless territory of two indigenous groups, the Miskito and the Tawahka, who number approximately 6400 and 1100 people, respectively, in the watershed (Fig. 1) (McSweeney 2002). Typical of many other communities with subsistence-based livelihoods, the Miskito and Tawahka villages of the Patuca River are dependent on riverine and riparian ecosystems for navigation, agriculture, artisanal fisheries, bush meat, edible and useful plants, and drinking water (McSweeney 2002, 2004).

As is the case for most rivers in Central America, ecological data are largely unavailable for the Patuca River. As a result, we drew heavily on

Fig. 1. The Patuca River and its location in the country of Honduras in Central America. The study reach stretched from just below the dam site near Nueva Palestina to the village of Kuhrpa in the coastal plain. The hydrological gauging site at Cayetano mentioned in the text was located just below the dam site, whereas the one at Kuhrpa was located at the village with the same name.



traditional ecological knowledge (TEK; "all types of knowledge about the environment derived from experience and traditions of a particular group of people" (Usher 2000)) and expert understanding of basic riverine processes as primary information sources to aid the development of environmental flow recommendations for the river. Traditional ecological knowledge has been used frequently in other contexts to inform policy and natural resource management decisions and to incorporate the concerns of local communities (e.g., Klubnikin et al. 2000, Ellis 2005). An abundance of research has reinforced the idea that local and traditional fact-based claims can be scientifically accurate. For example, previous works comparing traditional knowledge to empirical scientific studies have shown that fishermen can recognize taxa, can have accurate knowledge on both fish behavioral traits (Morrill 1967, Johannes 1978, 1981) and spatiotemporal changes in fish assemblage composition across seasons (Poizat and Baran 1997), and can accurately attribute causation to complex limnological occurrences (Calheiros et al. 2000). These studies demonstrate that, when collected carefully, TEK has the potential to be a highly accurate source of information.

Below, we present the process used to incorporate TEK and expert knowledge into an environmental flow prescription for the Patuca River. The goal of this environmental flow recommendation was to define the suite of flow conditions that must be maintained to preserve important flow-dependent ecological and social characteristics of the Patuca River. After describing the methods used, we present our findings and flow recommendation, and discuss how this project informs the debate over sustainable hydropower.

BACKGROUND AND SITE DESCRIPTION

The Empresa Nacional de Energía Eléctrica (ENEE) is the quasi-governmental organization responsible for electric energy generation and delivery in Honduras that is overseeing the planning and design of Patuca 3. In 2006, ENEE entered into a Memorandum of Understanding (MOU) with The Nature Conservancy (TNC) to facilitate the development of environmental flow recommendations by ENEE for the design and operation of the planned dam on the Patuca River (Patuca 3). The role of TNC was to provide ENEE with essential exposure to practices and approaches relevant to ecologically sustainable water management. Both parties agreed that the end-product would be an environmental flow recommendation that would inform Patuca 3's environmental impact assessment. The MOU also stated that TNC's participation did not imply an endorsement of the dam and that the final flow recommendation would be ENEE's product exclusively.

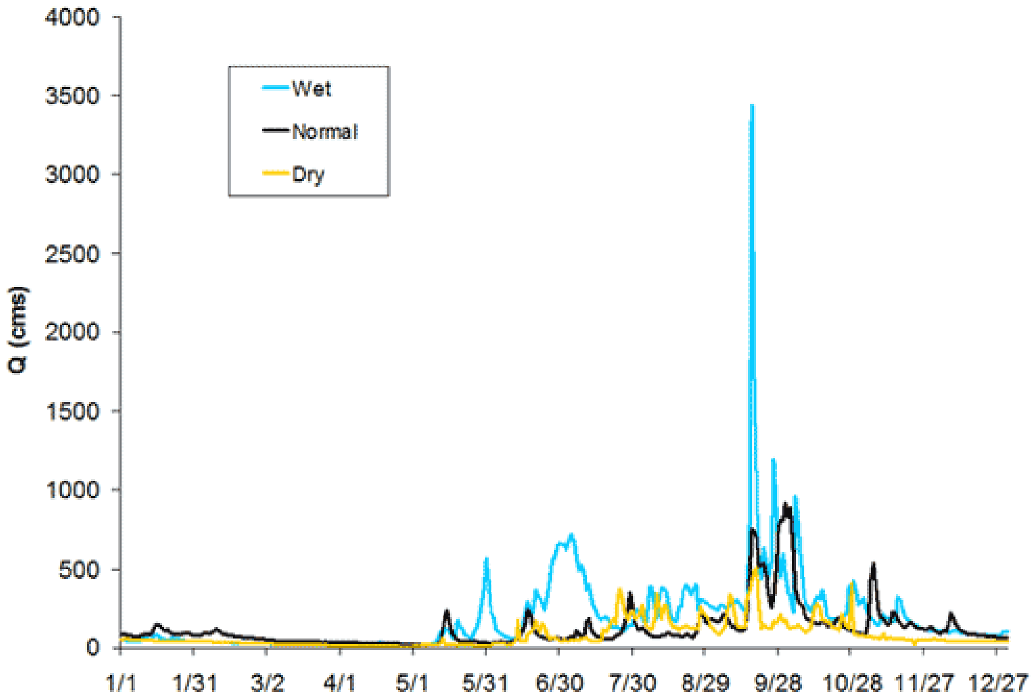
The Patuca River begins at the confluence of the Guayape and Guayambre Rivers, and flows 465 km to the Caribbean Sea, with a drainage area of approximately 24 000 km^2 (Fig. 1). Approximately one-third of the basin has been deforested for cattle pasture, agriculture, and urban development, primarily in the headwaters above the proposed dam site. The low-elevation portions of the watershed are heavily forested and roadless except for the area very close to the coast, which has limited road access. The river flows through three large protected areas: Patuca National Park, the Tawahka-Asangni Biosphere Reserve, and the Rio Platano Biosphere Reserve (Fig. 1). The latter two protected areas were created in recognition of their unique cultural and biological diversity. Along with the contiguous forests on the Atlantic coast of Nicaragua, this region encompasses one of the largest roadless areas in Mesoamerica.

Precipitation in the Patuca basin is highly variable, both temporally and spatially. The basin is subject to an annual dry season between January and May, with most of the yearly precipitation occurring during the wet season from June to December. The low-elevation coastal plain receives nearly 3000 mm of rain a year, but because the Honduran Central Highlands are situated between the Caribbean and the upper watershed and block frontal storms, the steep headwaters (more than 2000 m above sea level) receive only 900 mm of rain a year. The seasonality of rainfall leads to a corresponding seasonality in river discharge (Fig. 2). The hydrology of the Patuca River also displays considerable between-year variability, with individual years that range from very dry to very wet (Fig. 2). The area also occasionally experiences severe storm events, such as when Hurricane Mitch deposited up to 1.8 m of rain in some locations in October 1998 and caused the middle reaches of the Patuca to rise 14 m within a few days (DeVries 2000). The floods associated with Mitch were among the most extreme on record anywhere in the world (Smith et al. 2002), and had a strong influence on the Patuca ecosystem and the human communities that depend upon it (McSweeney 2002).

The Patuca is a large river by Central American standards, with an average instantaneous yearly discharge of 135 cubic meters per second m^3/s at Cayetano near the dam site, and 429 m^3/s at Kuhrpa downstream (Fig. 1). Mean monthly discharges are as great as 232 m^3/s and 683 m^3/s, respectively, at these locations in October. The river below the dam site flows through a tightly constrained valley with little floodplain until it reaches the confluence with Rio Wampu. In the valley, the river channel alternates between heavily boulder-strewn rapids and long trench pools. Below Rio Wampu, the river enters the coastal plain and flows with wide meanders across an extensive floodplain, exposing large sand bars during the dry season.

Nine communities—three indigenous Miskito, five indigenous Tawahka, and one Mestizo—are located along the banks of the river between Kuhrpa and Nueva Palestina (Fig. 1). Approximately 300 Mestizo settlers also live in squatter homesteads along the river within Patuca National Park. The indigenous communities on the middle Patuca subsist on agroforestry and slash-and-burn agriculture supplemented by animal husbandry, fishing, hunting, and foraging. Agriculture is concentrated on the active flood plain, and the river is an important source of water for cooking and bathing, with drinking water coming from

Fig. 2. Representative dry-, normal-, and wet-year hydrographs for the Patuca River at Cayetano, showing the stable low-flow conditions of dry season (January to May), and higher base flow and more variable hydrological conditions of the wet season (June to December). Q = discharge measured in cubic meters per second.



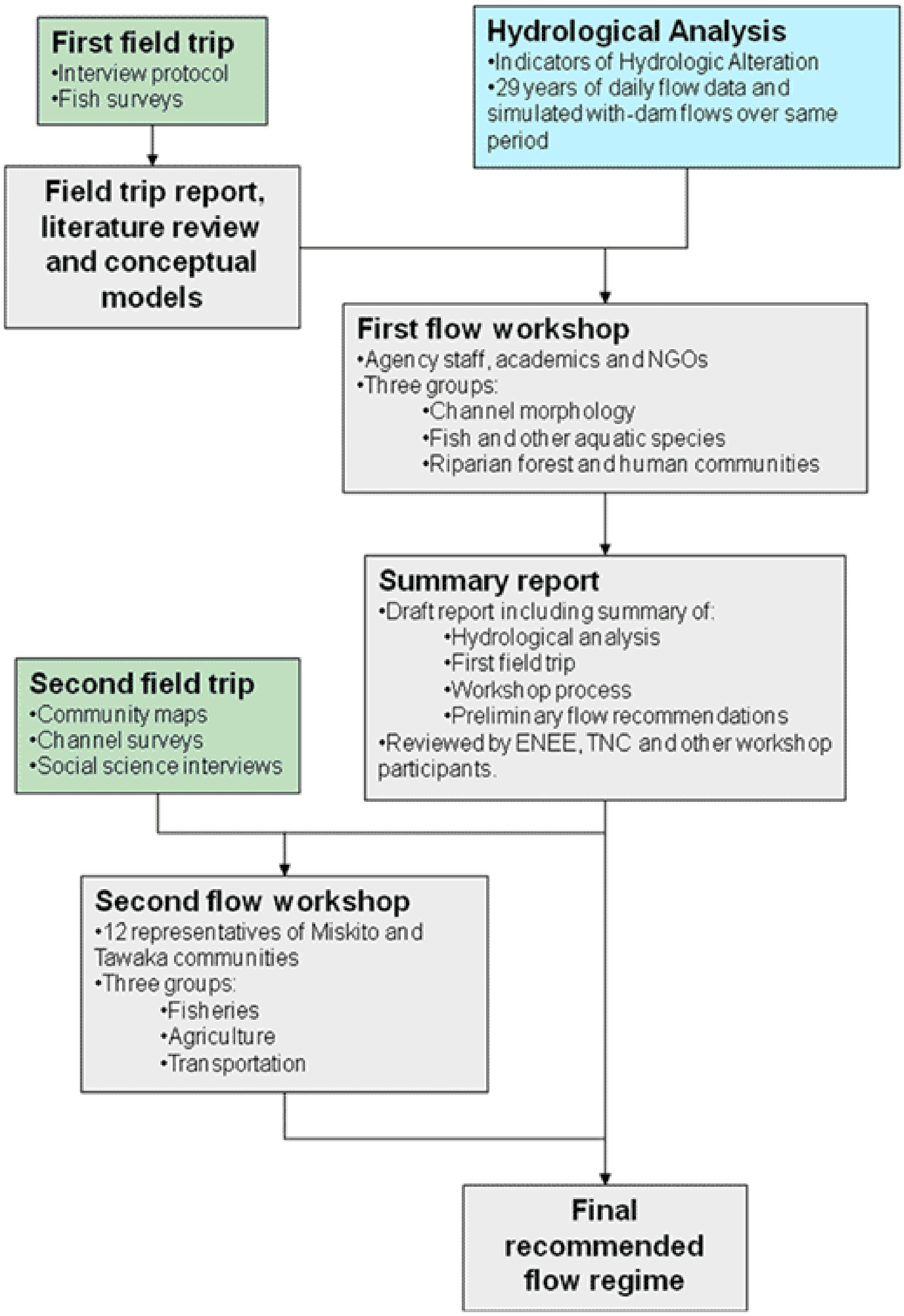
tributaries. Communities along the waterway depend heavily on the river for transportation, particularly for trade of cash crops (rice, cacao), gold, livestock, and forest products (McSweeney 2004). Transportation is accomplished using dugout canoes, locally known as “pipantes,” carved from large rainforest trees. Commercial pipantes are equipped with 40 or 60 hp outboard boat engines. The main upstream trading destination is Nueva Palestina, which, although a longer trip than the downstream trading center of Wampusirpe, is economically more beneficial because products are cheaper when purchased there.

The proposed site of the Patuca 3 hydropower dam lies 5 km below the confluence of the Guayambre and Guayape rivers (Fig. 1). In October 2006, ENEE signed a MOU with Taipower to design and construct the proposed dam. Taipower hired the engineering firm Sinotech to complete feasibility studies and design the project. Approximately half of the entire Patuca watershed (12 000 km^2) lies above the dam site. The dam will have a height of 60 m and a width of 208 m at its crest. The reservoir will flood portions of both the lower Guayambre and Guayape Rivers, will have a surface area of 72 km^2, and a volume of 1.2 billion cubic meters. The proposed power plant includes two turbines and a total generator capacity of 104 MW. In the current design, the turbines are sized for maximum discharge of 135 m^3/s each, and each turbine cannot operate efficiently below 40 m^3/s (Sinotech Engineering Consultants 2007).

METHODS

The process to develop environmental flow recommendations for the Patuca River involved multiple steps and included hydrological analysis, field trips to gather TEK, and workshops (Fig. 3).

Fig. 3. Flow chart showing process used in this study to prescribe an environmental flow regime for the Patuca River.



Hydrological Analysis

To understand how future dam operations will likely alter the hydrology of the Patuca River, we used the Indicators of Hydrologic Alteration (IHA) software to compare the natural flow regime (herein referred to as the “unregulated” state) to a computer-simulated managed flow regime with no environmental flows (herein referred to as “regulated”). The IHA software is a hydrological assessment tool that uses daily flow data to describe and assess human-induced changes to the natural flow regime (Richter et al. 1996, Mathews and Richter 2007). The IHA output describes a river’s flow regime in terms of environmental flow components (EFCs), which include low flows throughout the year, high-flow pulses, and floods. The EFCs can form the constituents of a recommended environmental flow regime (Mathews and Richter 2007). For the IHA analysis, the unregulated flow data came from an ENEE gauge near the dam site (Cayetano) with 29 years of daily flow data, whereas the regulated flow data were produced from Sinotech’s operations model that simulated with-dam daily flows for the same location and time period (1973–2001). Because only the model results and not the model itself were available to us, we were unable to conduct independent quality checks on their estimates. Corresponding data were also provided for a gauge near Kuhrpa.

The historical record of daily flow magnitudes available for Cayetano exhibits a range of variability from which we defined “dry,” “normal,” and “wet” year types—a central theme around which the final flow recommendations were organized (Fig. 2). Year type was defined by finding the average and standard deviation of all annual flows for the available 29 years of data. Dry years were defined as those lower than one standard deviation below the average annual flow; wet years were defined as those greater than one standard deviation above the average annual flow. This simple approach to defining year types was used only to characterize the variability of flow between years. Further research is necessary to evaluate whether this definition of year types is of significance to ecological communities.

Field Reconnaissance

Two field trips were conducted to provide information about the Patuca ecosystem and human uses of the river. The first field trip was conducted in August 2006 (a period of relatively high base flows) and the second occurred in May 2007 (a period of low base flows). During the first field trip, a group of 12 researchers traveled a 250-km stretch of the middle Patuca by dugout canoe, visiting 11 communities from Agua Caliente (5 km upstream of Nueva Palestina) to Kuhrpa (Fig. 1). The researchers used standard questionnaires to conduct interviews to document communities’ socioeconomic characteristics, utilitarian and cultural values of the river, and TEK about the river’s hydrology, geomorphology, aquatic and riparian fauna, and ecosystems (see Appendix for questionnaire). The questionnaires were designed to elucidate fact-based knowledge about the river’s flow dynamics; channel morphology; aquatic community composition; the diet, habitats, and reproductive details for important fish species; and value-based knowledge about aspects of the river and floodplain that have specific value to communities for economic, social, or cultural reasons. Key informants in each community were identified through a process of peer selection by village leaders. Environmental engineers collected information about socioeconomic values of the river, hydrology, and geomorphology; a soil ecologist and a forester assessed the riparian ecosystems; and two aquatic ecologists investigated the aquatic fauna and ecosystem. The assessment of aquatic community composition from interviews with fishermen was facilitated by the use of laminated pictures of species thought to occur in the area from species lists derived from a preliminary literature review.

The objectives of the second field trip were to: (1) conduct more interviews to validate information from the first trip; and (2) gather more information about how different flow levels affect the villages along the river. For the second objective, community leaders were asked to draw bird’s-eye view maps of characteristic water levels at different times of year relative to important geographic features (such as the locations of civic areas, crops, and fishing grounds), and to comment on the advantages and disadvantages of given water levels for their livelihoods. The mapping was always accomplished by groups of people, most of whom were men between the ages of 20 and 55 years of age, and was facilitated by a PhD anthropologist.

This proved an efficient way of eliciting information about the relationships between the communities and the river that fit within the limited time available for data collection. Data about transportation were gathered through interviews with boat captains from villages along the study reach.

Flow Workshops and the Recommended Flow Regime

Flow workshops were modeled after the Savannah Process (Richter et al. 2006), in which small breakout groups focus on the environmental flow requirements of various components of the river system. The breakout groups then reconvene and develop a "unified flow recommendation." An initial flow workshop, held in December 2006, brought together eight environmental engineers, an agriculture engineer, and a hydrologist from ENEE; two Honduran conservation professionals from TNC; seven Honduran experts in aquatic ecology, hydrology, water quality, and forestry; international experts in wetlands ecology, hydrology, aquatic ecosystems, and geomorphology; and seven individuals from Honduran non-governmental organizations and government agencies that work in the Patuca River area. These individuals were identified by ENEE with recommendations from the Honduran academic and government community. The workshop was facilitated by TNC staff members with experience in applying the Savannah Process, and workgroups were led by international experts with experience in developing environmental flow recommendations. Participants were asked to focus exclusively on the flow levels and flow components required to maintain both a healthy ecosystem and downstream human communities (i.e., participants were not asked to consider trade-offs with hydropower production). Workshop participants drew from three primary sources of information available in reports and presentations given at the beginning of the workshop: (1) basic information on climate, the watershed, hydrology, and technical information about the proposed dam; (2) the hydrological analysis comparing unregulated and regulated (simulated) flow regimes; and (3) summaries of information collected on the first field trip, presented in a report that included conceptual models of the relationships between the flow regime and fish species with different characteristic life-history types (e.g., pair-brooding cichlids, amphidromous migratory species, catadromous species, and marine fishes that inhabit freshwater).

Three working groups were formed that focused on: (1) fish and other aquatic organisms; (2) terrestrial resources, human communities, and riparian forests; and (3) channel morphology. Because none of the participants in the first workshop were experts on transportation, we addressed this important river value in a second workshop (see below). Each working group developed its own set of hydrological recommendations for the components of concern. The recommended EFCs were described in terms of magnitude, timing, duration, and frequency. Working groups documented their assumptions about links between the EFC and riverine processes for each recommendation they made. Participants also identified the most important uncertainties and priorities for further research.

The three groups' recommendations were transferred into the Regime Prescription Tool (HEC-RPT; http://www.hec.usace.army.mil/software/hec-rpt/). The HEC-RPT allows the visualization of alternative hydrograph scenarios, and in this case, was used to overlay the proposed hydrographs of different workgroups for comparison. Using the HEC-RPT, we developed a unified recommended hydrograph that synthesized the three workgroups' recommended hydrographs, retaining the most important elements of each.

A second environmental flow assessment workshop (August 2007) was structured to incorporate indigenous community members' knowledge about the river. Twelve individuals, representing Tawahka, Miskito, and Mestizo communities—one or more from each community in the study reach—attended the workshop. The second workshop was facilitated by the same TNC staff members as the first, and breakout groups were led by members of the field reconnaissance teams that had conducted field work. Three breakout groups focused on agriculture, fisheries, and transportation (important community values identified during the first field trip). In breakout groups, community members identified river processes and conditions that either benefited or created difficulties for their livelihoods.

Several methods were used during the second workshop to facilitate the discussion about flow levels. First, we projected photos of well-known river locations, and community members annotated the photos to show water heights associated with important river conditions (Fig. 4). We also used hand-drawn maps to show how different flood levels affected crops and communities (similar to the technique used on the second field trip). Finally, the transportation group drew a map of the river and identified the most challenging passage points for boat traffic. In all cases, we asked community members to attribute their annotated pictures and maps with flows from recent months, so that specific flow levels associated with those dates could be identified and incorporated into our environmental flow prescription.

Based on a synthesis of information gathered in this second workshop, we adjusted the unified hydrograph created after the first workshop. This resulted in our final recommended flow regime for the Patuca River below the proposed Patuca 3, which was formalized in a report that condensed all findings from the field trips and workshops to justify the ranges of recommended flow values, and included a list of critical questions and research priorities.

Feasibility Analysis of Flow Recommendations

Using daily discharge data for unregulated inflow and simulated with-dam outflow, we developed a simple spreadsheet model that estimated the reservoir volume associated with alternative operations scenarios. These operations scenarios focused on regulated (derived from Sinotech's operations model and simulating the flow with dam operations) and environmental flow regimes (the regulated hydrograph with the recommended EFCs added). To test the feasibility of implementing the recommended EFCs we compared how the regulated and environmental flow regimes affected reservoir levels within the model. As a simple rule, for the environmental flow regime the model released high-flow pulses only after a high-flow pulse entered the reservoir. High-flow pulses were defined as sharp increases from base flow that exceeded the lower boundary of the EFC magnitude ranges for high-flow pulses (Table 1). After a high-flow pulse entered the reservoir, the model released a high-flow pulse that matched the magnitude and duration of the inflow pulse up to the maximum values of the recommended ranges for the EFCs (Table 1). The model released high-flow pulses until the maximum recommended number of pulses for a wet year had been released. Thus, releasing high-flow pulses within this model did not require a priori designation of year type (e.g., dry, normal, wet), but because the model released pulses based on inflow events, the model did tend to release more pulses in wet years than dry years.

RESULTS

Diverse data sources were used to develop flow recommendations for the Patuca River below Patuca 3, including 29 years of hydrological records; published and gray literature; TEK gathered in 24 interviews with 45 community members; direct observation of channel morphology, forestry, and agriculture; and the opinions of 18 specialists and 12 community leaders who participated in workshops. Only those findings with direct pertinence to the flow recommendation are presented below.

Hydrological Analysis

Based on the analysis of annual flows within the 29-year record, we identified four "dry" years (1973, 1985, 2000, and 2001) and six "wet" years (1979, 1982, 1993, 1995, 1998, and 1999). The remaining 19 years were classified as "normal."

The IHA analysis for Cayetano indicated that the greatest hydrological alterations with dam operations will likely be: (1) a decline of high-flow pulses during the wet season from an average of 10 per year to 5 per year; and (2) elevated low flows during the dry season (Fig. 5). With unregulated hydrology, base flows in March through May averaged between 20 and 30 m^3/s, whereas with regulated hydrology, the base flows are predicted to be between 65 and 70 m^3/s as a result of releases of water stored during the prior wet season to generate electricity. Review of unregulated and regulated hydrographs indicates that much of the loss of high-flow pulses will occur in the transition between the dry and wet seasons (e.g., June through September) in the time that the reservoir refills after the dry-season drawdown. Dam operations will apparently have little or no effect on floods and late wet-season flow levels (Fig. 5).

Over the 29-year hydrological record, approximately one-third of the annual discharge at Kuhrpa was derived from the portion of the watershed above Cayetano (i.e., the portion of the drainage area above the proposed dam). Only in the months of June and July did more than half the flow at Kuhrpa derive

Fig. 4. Important flow levels were established in workshops with community members by annotating photographs of familiar locations along the river (top). In this case, a community member from Pimienta Village is indicating the level that Hurricane Mitch reached by pointing out a specific palm tree that he used as a visual reference during the storm. The results (bottom) helped establish the positive and negative importance of different flow levels for values of the river from the perspectives of community members.

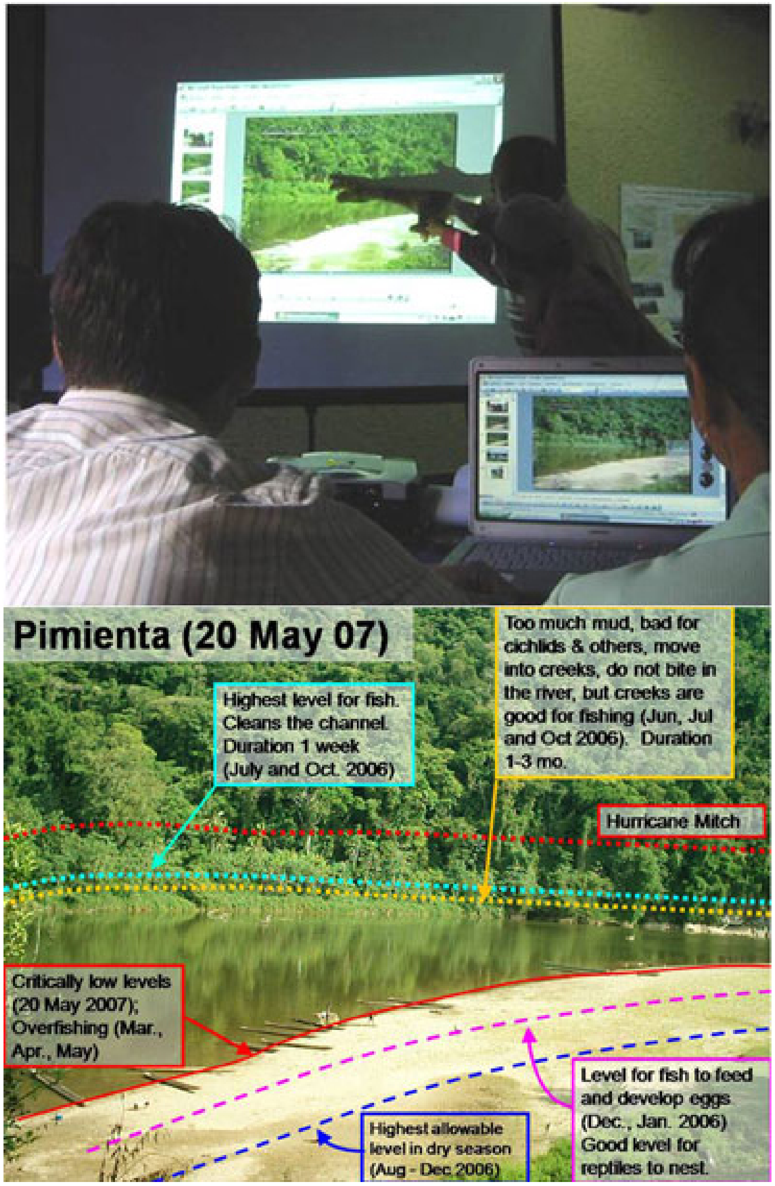


Table 1. Unified flow recommendation's high-flow pulses and floods for dry, normal, and wet years. EFC = environmental flow component.

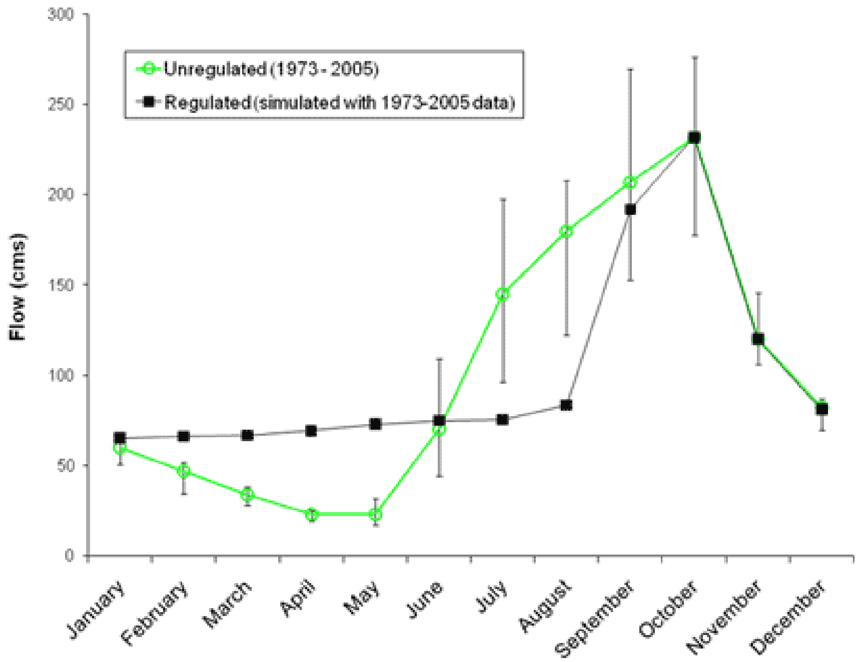
EFC	Season	Year type	Magnitude (m^3/s)	Frequency	Duration	Example flow-ecology links
Early wet-season high-flow pulses	June 1–July 15	Dry Normal Wet	125–170 125–300 125–500	≥ 1 ≥ 2 ≥ 2	4–10 d	Provide cues to migratory fish Reduce predation on juveniles spawned during dry season
Mid wet-season high-flow pulses	July 16–Nov. 14	Dry Normal Wet	200–600 200–900 200–900	≥ 4 ≥ 4 ≥ 4	4–10 d	Trigger spawning activity by migratory fish Fish gain access to channel margin habitat
Late wet-season high-flow pulses	Nov. 15–Dec. 15	Dry Normal Wet	125–170 125–300 150–350	≥ 1 ≥ 2 ≥ 2	4–10 d	Migration and juvenile dispersal for late-spawning fish Replenish beaches for reptile nesting
Flood	Aug. 15–Oct. 30	Dry Normal Wet	- 1000–2000 2000–3500	- ≥ 1 ≥ 1	- 15–40 d	Sediment transport and maintain channel form Create floodplain topography Provide fish access to floodplain Disperse tree seeds Deposit sediment on agricultural fields

from above the dam site; for most months, the proportion was approximately 20%. The IHA analysis indicated that the primary hydrological alteration likely at Kuhrpa is an increase in low flows during the dry season, with relatively minor or no effect on other flow components. Thus, the aspects of our flow recommendations that address high-flow pulses and floods pertain primarily to the reach between the dam site and the confluence of Rio Wampu (Fig. 1).

Aquatic Ecological Communities

Fisherman responses about aquatic community composition and life-history traits were cross-referenced against existing species lists, published literature, and the opinions of expert taxonomists before the results presented here were finalized. However, we do not consider this to be a definitive list because we were unable to collect voucher specimens to confirm species identities. Rather, we consider this to represent a possible list of commonly captured species that are likely to occur in the Patuca River. Twenty-six fish species in at least 17 families were reported by community members, and 17 non-piscine aquatic species were reported to be important to communities (Table 2). Most of these species were used as food sources, indicating that the communities living in the middle Patuca use a diversity of riverine animals for subsistence. The most important species in the fishery were the blackbelt cichlid (*Vieja maculicauda*) and feral populations of non-indigenous African tilapia (from photo vouchers appears to be Nile tilapia, *Oreochromis niloticus*). Other important food fishes include the wolf cichlid (*Parachromis dovii*), several snook species that inhabit fresh water and salt water (*Centropomus undecimalis* and *C. ensiferus*), and two mullet species, the cuyamel (*Joturus pichardi*) and tepemechín (*Agonostomus monticola*). A number of non-piscine aquatic and semi-aquatic organisms are also important to the human and biological communities of the Patuca River. These include at least three freshwater shrimp species, two crab species, one mussel species (a food of last resort), and a number of reptiles including the green iguana

Fig. 5. Comparison of the median monthly flow values for the unregulated flow regime (green; error bars bracket the middle third of the distribution) and the regulated (simulated) flow regime (black) at Cayetano. The IHA analysis indicated that the greatest hydrological alterations will be elevated low flows during the dry season, and a decline in high-flow pulses during the early part of the wet season when the reservoir is filling to capacity.



(*Iguana iguana*) and five species of turtles that are eaten by community members (Table 2).

Two characteristics of the aquatic communities identified in workshops as highly important to the creation of a flow prescription for Patuca 3 were: (1) migratory life cycles of fishes; and (2) reproductive timing and habitats of fishes and herpetofauna. At least eight of the species reported are migratory with life cycles that integrate freshwater and saltwater environments (Table 2). Of these, four have catadromous life cycles where the adults live in freshwater and migrate to the coast to spawn and then either die (as does the American eel, *A. rostrata*) or migrate back upstream (as does cuyamel). The other four migratory species have amphidromous life cycles where the adults live entirely in freshwater, but lay eggs that are carried by the river to hatch in or just upstream of the estuary, where the young feed until they migrate upstream to live the rest of their lives in freshwater (McDowall 1992). All of these species occupy large headwater streams as adults, and thus require unimpeded migration corridors between the mountains and the sea to persist in upstream habitats (March et al. 2003). Based on research elsewhere in the region, spawning and downstream migration of the species in the study area are thought to correspond with wet-season flood events (Cruz 1987, 1989, Benstead et al. 1999, 2000), and upstream post-larval migration has been documented to occur in large mixed-species aggregations in the transition between the wet and dry season (Gilbert and Kelso 1971, Winemiller and Leslie 1992). Based on this knowledge of life histories, we identified three aspects of flow to which migratory fauna were likely to be most sensitive: (1) the timing of transitions between the dry and wet season and the onset of flooding; (2) the magnitudes of dry and wet season base flows and high flow events; and (3) the variability of flow conditions in the early wet season that may serve as cues for migrations.

Table 2. Fish species and some of the other aquatic organisms reported by the fishermen interviewed, with information on their reproductive habits, migratory status, and importance to local fisheries. Fisheries codes are: rarely captured (R), occasionally captured (O), seasonally important (S), and commonly captured (C).

Family	Scientific name	Common name	Reproduce when?	Reproduce where?	Migratory?	Fishery
Carcharhinidae	*Carcharhinus leucas*	Bull shark	?	Sea	No	R
Pristidae	*Pristis pristis*	Common sawfish	?	?	No	R
Anguillidae	*Anguilla rostrata*	American eel		Sea	Catadromous	O
Megalopidae	*Megalops atlanticus*	Tarpon	*?*	Sea	No	O
Characidae	*Astyanax aeneus*	Central tetra		?	No	O
Ictaluridae	*Ictalurus furcatus*	Blue catfish	June–Aug., Nov.–Jan.	?	No	C
Pimelodidae	*Rhamdia* spp.	Chulin	June–Aug.	?	No	C
Poeciliidae	*Poecilia gilli*	Molly	All year; peak May–June	?	No	S
Centropomidae	*Centropomus ensiferus*	Swordspine snook	Eggs Oct.–Jan.	Sea	No	C
Centropomidae	*Centropomus undecimalis*	Common snook	Eggs Oct.–Jan.	Sea	No	C
Lutjanidae	*Lutjanus griseus*	Gray snapper	?	?	Sea	O
Gerreidae	*Eugerres spp.*	Mojarra	?	?	No	O
Haemulidae	*Pomadasys crocro*	Burro grunt	?	?	Amphidromous	O
Cichlidae	*Amhpilophus alfari*	Pastel cichlid	Feb.–April	River banks	No	O
Cichlidae	*Amphilophus longimanus*	Red breast cichlid	Feb.–April	River banks	No	C
Cichlidae	*Archocentrus spilurus*	Blue eye cichlid	Feb.–April, May	River banks	No	O
Cichlidae	*Herotilapia multispinosa*	Rainbow cichlid	Feb.–April	River banks, creeks	No	?
Cichlidae	*Oreochromis niloticus*	Nile tilapia	Feb.–April	River banks	No	C
Cichlidae	*Parachromis dovii*	Wolf cichlid	Feb.–April	River banks	Local movements	C
Cichlidae	*Parachromis managuensis*	Jaguar cichlid	Feb.–April	River banks, creeks	No	O

(con'd)

Cichlidae	*Vieja maculicauda*	Blackbelt cichlid	Feb.–April	River banks, creeks	No	C
Mugilidae	*Agonostomus monticola*	Mountain mullet	Eggs in dry, go to sea in wet	Puts eggs under rocks	Catadromous and/or amphidromous	S
Mugilidae	*Joturus pichardi*	Bobo mullet	Eggs in dry, migrate Aug.–Sep.; return Nov.	Estuary	Catadromous	S
Eleotridae	*Gobiomorus dormitor*	Bigmouth sleeper	Eggs in dry	Deep pools	Amphidromous	O
Gobiidae	*Awaous banana*	Green river goby	?	Deep pools	Amphidromous	O
Non-fish taxa						
Palaemonidae	*Macrobrachium carcinus*	Macrobrachium	Wet season		Amphidromous	O
Atyidae	*Atya sp.*	Atyid shrimp	Wet season		Amphidromous	?
Portunidae	*Callinectes* sp.	Crab				O
Gecarcinidae	*Cardisoma guanhumi*	Land crab	June	Streams	?	O
Alligatoridae	*Caiman crocodilus*	Spectacled caiman	?	Exposed sand bars near river	No	?
Crocodylidae	*Crocodylus acutus*	Crocodile	Dry	Exposed sand bars near river	No	?
Kinosternidae	*Kinosternon leucostomun*	Wood turtle				?
Emydidae	*Rhinoclemmiys funera*	White-lipped mud turtle				S
Emydidae	*Trachemys scripta*	Jicotea				S
Iguanidae	*Iguana iguana*	Green iguana	March	Exposed sand bars near river	No	S

Interviews with fishermen revealed important patterns in the reproductive habitats and times of reproduction for many aquatic organisms in the Patuca River. Most of aquatic species identified from the middle Patuca were reported to either reproduce during the dry season or to have eggs in development within the body during this period (Table 2). Species reported to reproduce during the dry season include all of the fishes in the family Cichlidae, as well as turtles, iguanas, and crocodiles. Turtles were reported by almost all respondents to reproduce on sand bars in the river channel in the month of February, whereas iguanas were reported to nest on bars in March. Given the prediction of higher dry-season base flows, the availability of nesting beaches for these reptiles may become more limited. All cichlids in the study area (except tilapia) are nest brooders, where adult breeding pairs create and defend nests near the banks where their eggs and young develop. Should peaking flows be released from the Patuca 3 dam to generate electricity during times of greatest electricity demand, bank habitats will experience rapid daily fluctuations in water levels, potentially disrupting nesting environments. From these findings, we identified two additional aspects of flow likely to be important to maintenance of aquatic communities: (1) timing of dry-season base flows; and (2) dry-season daily flow variability potentially associated with peaking operation. Officials of ENEE were uncertain about the degree to which daily peaking operations will occur, so we drafted general guidelines to address peaking operation as a precaution (not presented here).

Importance of Floodplains

Communities living along the Patuca River downstream of the dam site use floodplains heavily for agricultural activities and collection of useful plants and forest products. Most of the important staple and cash crops are planted on the floodplain within the area that is periodically inundated by floodwaters. These include bananas, plantains, rice, beans, and cacao. The annual crops are planted at specific times of year in response to the annual cycle of drought and rains. Community members reported both positive and negative interactions between river flows and agricultural productivity. Positive influences include the deposition of nutrient-rich sediments during wet-season floods that increase the fertility of floodplain fields. For example, the agricultural working group during the second workshop reported that flooding in October was correlated with good harvests of beans in the following April. Floods were also observed to reduce fungi that attack cacao trees. However, it was reported that large floods can be detrimental in that they can damage crops planted near the river, particularly maize, bananas, and rice. Because Patuca 3 is not intended to provide flood control, which was confirmed by the IHA analysis showing no change in flood magnitudes or frequencies between the unregulated and regulated flow regimes, the dam is unlikely to reduce the damages associated with large flood events.

Transportation

According to boat captains and community leaders, about 60% of boat traffic on the Patuca River is for business and trade, 30% is for public transportation, and the remaining 10% is for other travel. River trade takes place throughout the year. In the dry season, low river levels can make travel difficult and expensive. Low water levels cause trips to become much longer and introduce the possibility of damaging boats and engine propellers on boulders and exposed logs, and causing injury or death to passengers. The economic livelihoods of the communities of the middle Patuca are tied to their ability to transport goods on the river, thus the number of trips in the dry and wet seasons were reported to be roughly equal, although the seasonal variation of prices of the various products (butter, oil, tomato paste, soft drinks, etc.) do reflect the difficulties of navigating the river during the dry season.

Participants in the transportation working group identified six critical points of passage and numerous smaller challenges between Kuhrpa and Nueva Palestina. All but one of these obstructions were attributable to low water levels during the dry season. It was reported that a 1–2 m augmentation of flow levels above normal dry-season base flow level would be necessary to overcome these difficult barriers to passage and trade. In flow quantities, this translates to an increase of the mean dry-season base flow (range = 20–30 m^3/s at Cayetano) by 40–50 m^3/s to approximately 60–80 m^3/s. This 60–80 m^3/s range is similar to the predicted mean outflow from Patuca 3 during normal dry-season operation, suggesting that the dam may have a positive influence on transportation.

Robustness of TEK

It is important to examine the robustness of the TEK gathered and to identify potential biases that may affect our conclusions. Of particular importance are: (1) the accuracy of the facts shared by respondents, and (2) the variability of responses between individuals and communities. It is possible to assess the accuracy of some responses by cross-checking interview data against published scientific accounts. When we did this for fish life-history data, we concluded that fishermen were best at identifying ecological characteristics that are readily observable (e.g., they take place during the dry season when river water is clear), or that concern species that have high use value. For example, more than 80% of respondents correctly identified commonly captured resident cichlid fishes as reproductively active in the dry season, and more than 50% reported that tarpon and the two snook species originated in the sea and traveled long distances in the river channel. Yet, only one-third of respondents correctly identified tepemechín and cuyamel (both important food fishes) as animals that migrate during the wet season (Cruz 1987, 1989), and none accurately identified the other known migratory fishes and shrimps (Table 2). The failure to identify these species as migratory may be due to the fact that all of these species are amphidromous (so the adults are permanent residents of river habitats), that some of these species are cryptic, or that fishermen are unaware of what these fishes do when the water becomes turbid. Thus, without complementary knowledge from published reports and expert consultation, use of TEK alone would have led to a less complete understanding of important ecological traits of aquatic biota. Nevertheless, the knowledge gained from TEK was still of sufficient quality to formulate reasonable hypotheses about links between river flow and biota.

The variability of responses between interviews was subject dependent, but tended to vary little between individuals, ethnicities, or communities. For instance, the fundamental observations about where crops were located relative to the river channel, where major barriers to transportation were located, and what fishes were important varied little. Over 85% of respondents to agriculture surveys commented on the importance of flood sediments for fertilizing crops on the floodplain. More varied responses were recorded on more nuanced questions such as, “At what river level do floods become detrimental?” Nonetheless, much of the basic information used in the development of our environmental flow recommendations was collected within the first eight to ten interviews. More interviews after this served to (1) reinforce the information gained previously, and (2) provide insights into less obvious aspects ecosystems or flow links. Examples of insights gained from single respondents included the observation that floods help remove pests from cacao fields, and that the common sawfish (*Pristis pristis*) occurred in the Patuca River as recently as the early 1980s. Although important, these observations were not necessary to hypothesize the environmental flow links that were ultimately most useful to our recommendations.

Flow Recommendations

The unified flow recommendation was defined in terms of EFCs—including low flows for each month, high-flow pulses, and floods—that varied for dry, normal, and wet years. Each recommendation was based upon a hypothesized link between a given EFC and specific processes or resources in the river ecosystem (Tables 1 and 3, Fig. 6).

Feasibility Analysis

In all years except one, the spreadsheet model indicated that the reservoir would fill early in the wet season (15 August ± 8 d; mean and standard error). Thereafter, the daily flow would become run-of-the-river (e.g., outflow equals inflow). Because of this trend, in nearly all years the regulated hydrograph is predicted to provide all the recommended floods and late wet-season high-flow pulses.

With regulated hydrology, middle wet-season high-flow pulses are predicted to occur less frequently than they did naturally (Fig. 7). The recommended number of middle wet-season high-flow pulses occurred in 12 out of the 29 years of the simulated regulated flow record, suggesting that an environmental flow regime will need to add at least one middle wet-season high-flow pulse in approximately 60% of years. Dam operations are predicted to have a greater proportional impact on early wet-season high-flow pulses (Fig. 7). Whereas in the unregulated flow regime, at least two early wet-season pulses occurred in 83% of years, with regulated hydrology two of these events are predicted to occur in only 17% of years, and 70% of years are predicted to have no early wet-season high-flow pulse whatsoever.

Because early and middle wet-season high-flow pulses were predicted to be the EFCs most affected by dam operations (other than dry season low flows), we focused the feasibility analysis on these events. The spreadsheet model indicated that, in all but two years, adding the recommended number of early and middle wet-season high-flow pulses to the regulated hydrograph would have delayed the refilling of the reservoir (and onset of run-of-river conditions) by less than 8 d (Fig. 8). In the second-driest year on record, releasing the recommended number of high-flow pulses would have delayed reservoir refilling by 14 d. The driest year on record (2001) was the only one in which the reservoir was not predicted to refill with the regulated flow

Table 3. Unified flow recommendation's low flows for each month, for dry, normal, and wet years. Flow rates are cubic meters per second (m^3/s).

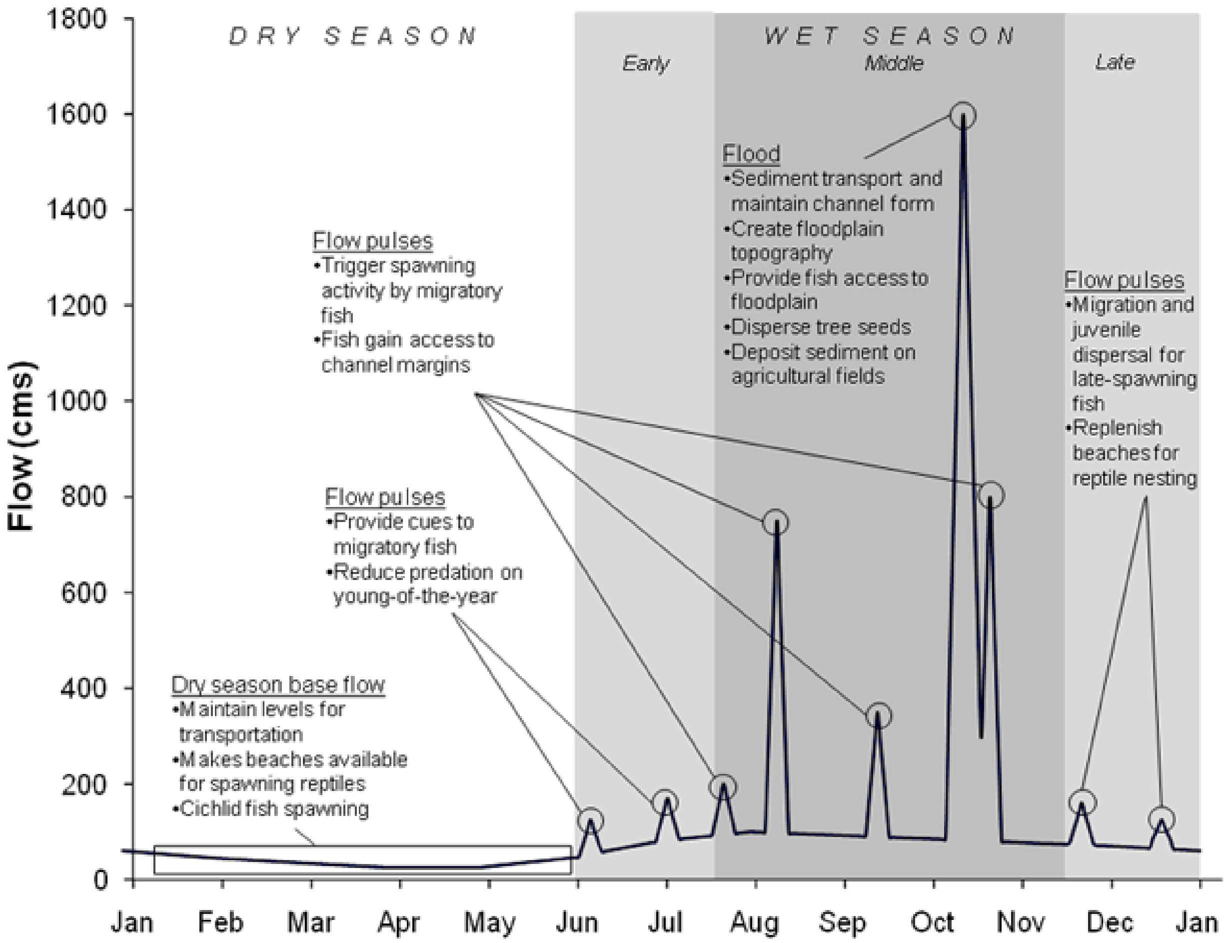
Month	Year Type: Dry	Normal	Wet	Example flow-ecology links
January	40–50	50–65	65–80	Jan. wet-year range considered "optimal" for transportation Beaches used by reptiles for nesting
February	30–35	35–50	55–65	Beaches used by reptiles for nesting
March	30	30–40	40–45	Flows below 30 m^3/s make transportation very difficult Cichlid fish spawning
April	30	30	30	Cichlid fish spawning
May	30	30	30–35	Cichlid fish spawning
June	30–35	35–60	70–90	Cues for spawning migratory species
July	45–55	60–90	125–135	Cues for spawning migratory species
August	45–70	80–115	120–150	
September	60–80	80–120	130–145	
October	90–100	100–130	130–145	
November	60–75	80–115	120–140	
December	45–60	65–85	85–120	Upstream migrations of juvenile migratory species may begin

regime. With 2001 hydrology, the reservoir releases would have passed below the threshold for power generation, and essentially become run-of-the-river with low flows on 4 February 2002. If an environmental flow regime had been released in 2001, this condition would have been reached on 5 January 2002. In both scenarios, the reservoir was predicted to begin generation on the same day (25 May 2002) and refill and become run-of-river on the same day (29 August 2002). Thus, in only 1 month of 1 year out of 29 years did releasing an environmental flow regime substantially affect simulated hydropower generation, as it increased a period of no generation from 110 d to 140 d.

DISCUSSION

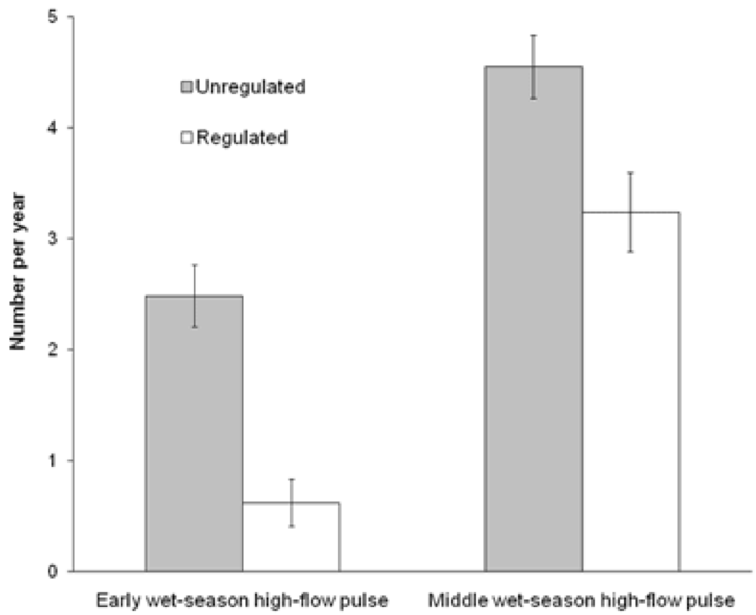
The multi-step process used to define an environmental flow prescription for the Patuca 3 dam linked patterns of historical flow with human values of the river and factors hypothesized as important for maintaining ecosystems, traditional economies, and cultural uses. Traditional ecological knowledge was essential to this process. The use of traditional and local ecological knowledge to form biological hypotheses and guide water resource management efforts has many precedents. For instance, Robertson and McGee (2003) used oral history data collected from local residents and natural resource managers to assemble a historical record of flood frequencies and ecology of a wetland in Australia, which were used to define scenarios

Fig. 6. A graphical summary of our environmental flow recommendation (dark black line) for a "normal" hydrological year. Flow magnitudes are shown on the y-axis, with month shown on the x-axis. Dry and wet seasons are indicated by white and gray shaded areas, respectively. Environmental flow components (base flow, high flow pulses, and floods) are labeled with some details of the important ecological and social values that they support. Ideally, the timing of flow pulses and floods will be adjusted as a function of reservoir inflow, rather than having the static shape presented here as an example.



for environmental decision support. The government of British Columbia, Canada drew extensively on local knowledge and expert opinion from public, aboriginal, and regulatory agency stakeholders to examine water allocation at 22 major hydropower sites, and to help select operating alternatives for dams (Failing et al. 2007). In fisheries management, fact-based knowledge from local and aboriginal fishermen has been shown to complement fisheries science by providing concordant and additional information about fish community composition, population viability, breeding and migration patterns, and behavioral ecology (Johannes 1978, 1981, Neis et al. 1999, Aswani and Hamilton 2004, Fraser et al. 2006, Garcia-Quijano 2007). Our environmental flow prescription was guided by the

Fig. 7. Frequency of early and middle wet-season high-flow pulses with the unregulated flow regime (gray bars) and the regulated flow regime (i.e., planned dam operations without releasing environmental flow recommendations). Error bars represent the standard error.

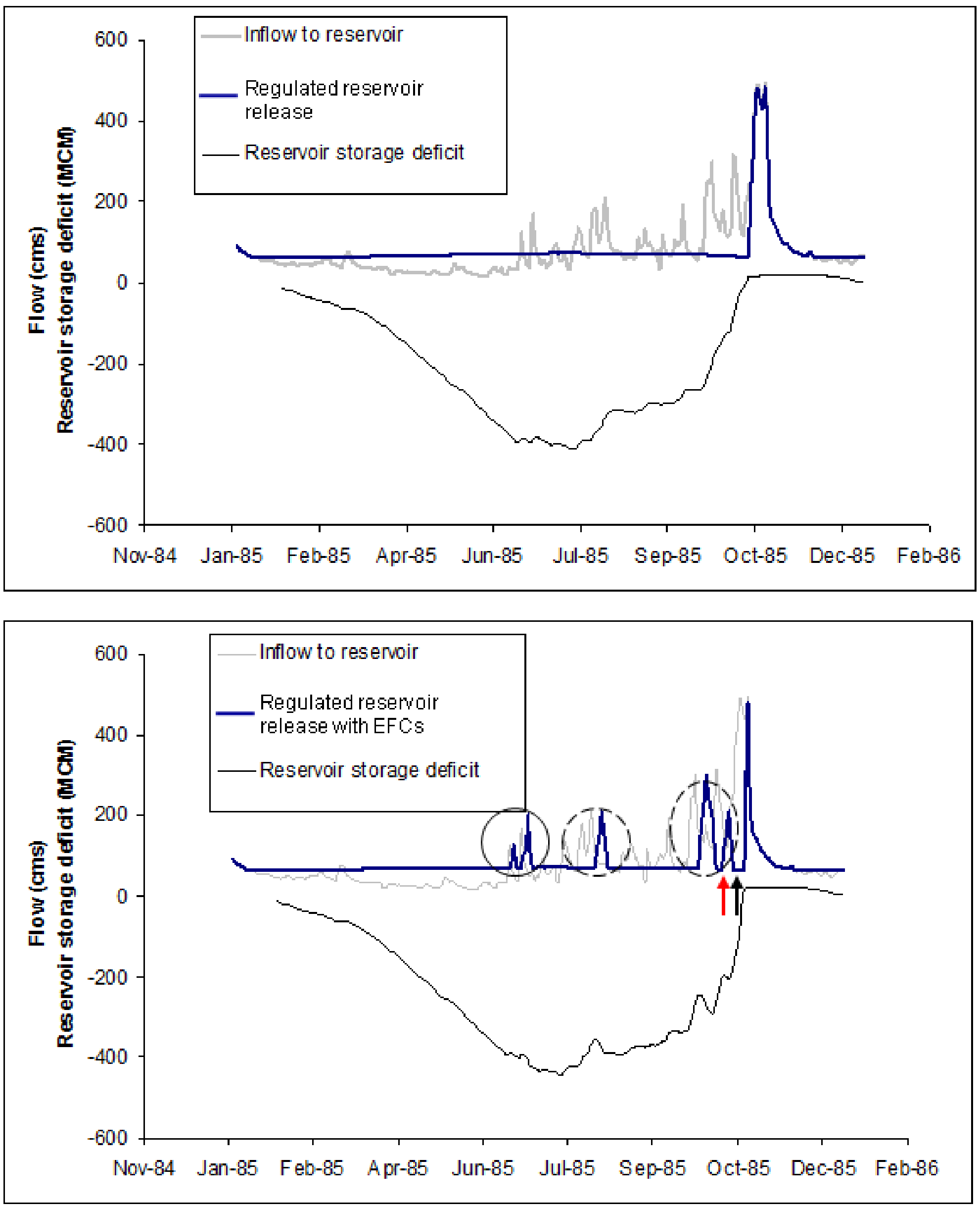


fact-based claims about riverine biota shared by the indigenous communities of the Patuca River, and by the value-based statements of how the river is important to communities.

Relative to the dominant paradigm of hypothesis testing using the scientific method, local and traditional ecological knowledge may seem subjective and uncertain. A substantial body of research identifies the limitations of humans to accurately translate their experiences into explicit information (Sterman 2000 *in* Fazey et al. 2006), because of human tendencies toward judgmental biases, difficulties in understanding complex probabilities, and limited abilities to learn about complex systems (Fazey et al. 2006). Bias can also arise when information providers desire specific outcomes that may be directly affected by the information they provide (Fazey et al. 2006). In our study, at least four factors may have affected the quality of information that we received. First, research visits to communities were relatively brief, averaging no more than 3 d in any one community. Second, ENEE’s past activities in the region, particularly their earlier attempts to develop another dam on the Patuca River main stem (a project that was strongly opposed by the communities of the middle Patuca; Gordon 2002) may have led to a strained context for gathering information. This tension was evident in public meetings that were held to describe the Patuca 3 project, but entered overtly into the interviews with fewer than eight of the 45 respondents. Third, all interviews were carried out in Spanish, the second language of the majority of respondents, whose primary languages were Miskitu or Tawahka. Interviewers were careful to seek clarification when difficulties arose, but this still may have led to translation errors. Finally, three-quarters of respondents were male, and thus our sample of river values reflects a gender-biased sample.

Researchers using TEK as an information source can guard against bias in numerous ways. These include subjecting information to scrutiny by an extended peer group, use of structured elicitation

Fig. 8. Results of our reservoir-filling mass-balance model. Top graph shows hydrology for 1985 (one of the driest years in the record), showing unregulated (inflow to reservoir; light gray), regulated (simulated outflow with dam operation; thick blue), and reservoir storage deficit (thin black line). The bottom graph shows an implementation scenario for an environmental flow regime for the same year that includes two early wet-season high-flow pulses (in solid circle) and three mid wet-season high-flow pulses (within dashed circles). These pulses delay reservoir filling by only 8 d. The red arrow indicates the day that the reservoir would have refilled under the regulated flow regime, and the black arrow indicates the day the reservoir would have refilled under the recommended environmental flow regime. MCM = million cubic meters.



methods, and gathering data in a way that separates direct observations (fact-based claims) from inference and value-based claims (Huntington 2000, Failing et al. 2007). In our study, we used a structured interview to collect factual information about river hydrology, geomorphology, and ecology. Our interviews were often done in a small group setting, which led to a limited form of scrutiny by peers, and workshops provided another forum for scrutiny by an extended peer group (Huntington 2000, Failing et al. 2007). We also subjected our species lists to review by taxonomists familiar with local biota. A cursory verification of the TEK gathered against factual reports from the scientific literature showed a relatively high degree of accuracy about those ecosystem characteristics that (1) were readily observable; and (2) about species with high use value. Within the communities of the middle Patuca River, variability between responses about the links among the river, flow patterns, and human well-being was relatively low, suggesting that our final environmental flow recommendation would have been substantially similar if only half the number of interviews had been conducted. Nonetheless, more interviews continued to strengthen our picture of how river flow influenced communities and ecosystems, thus we suggest that more interviews are still preferred when possible.

The use of TEK to formulate an environmental flow prescription was the only feasible option in this case to allow us to overcome the relative paucity of empirical scientific information for the study area, and to incorporate values of river-dependent communities into our recommendations. The fact-based claims that we recorded gave us the ability to assemble a set of ecological hypotheses, which were strengthened with input from local and international scientists. TEK also gave us detailed information about the social and economic values of the river and its hydrology to the people whose lives and livelihoods will be the most affected by the construction of Patuca 3. To complement the information generated through TEK, we drew on expert knowledge and used several simple but powerful assessment tools—IHA, HEC-RPT, and a spreadsheet reservoir model—to help us discern conflict areas and explore scenarios and solutions. Our product is a highly replicable example of how the Savannah Process can be applied in a data-poor context in a way that is responsive to the ecological and social realities of a specific place.

CONCLUSION: ENVIRONMENTAL FLOWS AND SUSTAINABLE HYDROPOWER

By combining TEK with several analytical tools within a flexible and adaptive process (Richter et al. 2006), we overcame limitations of scientific information to develop an environmental flow regime for the Patuca River below a proposed hydropower dam. This approach can be adapted for use at the numerous dams that already exist or are under development in this region and around the world that share similar data limitations. However, as explained below, ensuring the sustainability of future hydropower development in Central America will require more than the prescription and implementation of environmental flow regimes.

Assuming that our environmental flow recommendation is included in operations of the Patuca 3 dam, it will maintain important features of the natural hydrograph. This is a significant accomplishment in the search for solutions that manage water for people and nature. However, these recommendations —focused on a single river reach below a single proposed dam—reveal numerous limitations for pursuing sustainable hydropower at the scale of an individual hydropower project. For example, participants identified several potential impacts from the dam that environmental flows can only partially mitigate or cannot address at all. These impacts include barriers to fish migration into the upper watershed, capture of sediment, organic material, and nutrients within the reservoir, and changes to water quality and water temperatures.

Impacts to migratory biota are a particularly serious issue in terms of potential effects on riverine biota and human communities. Patuca 3 will create a large barrier in the channel that will exclude migratory species from a significant percentage of their range in the watershed (approximately half the watershed lies above the dam site). Possible results of the barrier include local extirpation of these species from the watershed above the dam (Holmquist et al. 1998, Greathouse et al. 2006) and reduced population size and/or genetic diversity, and thus reduced population viability (Shaffer 1981) of these species at the basin scale. Unfortunately, there is almost no available information on the relative importance of habitat above the dam site to migratory species, and so the degree that the dam will affect migratory species cannot be predicted accurately.

These issues emphasize the inherent limitations of pursuing sustainable hydropower at the scale of a single dam project. To fully address and mitigate the range of impacts caused by dam development, sustainable hydropower must be pursued across many project sites at larger spatial scales, such as an entire river basin or region (Harrison et al. 2007). Although the concept of sustainable hydropower is relatively new and still being debated, initial definitions from a wide range of sources support this assertion. For example, Ledec and Quintero (2003) emphasize that good site selection is by far the most effective form of "mitigation" for new dams. This acknowledges the limitations for dams to address impacts locally (e.g., impacts on migratory fish) and, therefore, the analysis of site selection should encompass a large spatial area to direct dam development toward the least damaging locations. The International Hydropower Association's Sustainable Assessment Protocol, which includes 20 criteria for evaluating new hydropower dams, also emphasizes the importance of taking a regional approach to site selection, such as avoiding river reaches with important environmental and cultural values, and favoring lower-value river reaches or those with flows already regulated by dams for development (International Hydropower Association 2006).

We suggest that much greater integration of conservation and infrastructure planning will be necessary to maximize the environmental and social sustainability of the proposed expansion of hydropower in Central America, and that environmental flow regimes are only one piece of a larger puzzle. Attempting to address issues of sustainability at the scale of individual dams, while ignoring larger geographic perspectives, will only slow, but not prevent, the continued degradation of aquatic ecosystems and resources that support biodiversity and rural and indigenous communities. Furthermore, an emphasis on the site scale misses opportunities that will benefit conservation, communities, and even hydropower developers. For example, hydropower development planning that is integrated with conservation planning can allow individual projects to contribute toward regional conservation goals as part of their mitigation strategies, thus achieving economies of scale not possible at the site scale. Hydropower projects selected through such a process are likely to face less controversy and opposition and thus have greater certainty and security for investors, developers, and governments.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol15/iss1/art6/responses/

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Appendix 1. Standard questionnaire used to interview community leaders and fisherpersons.

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