Environmental Flow Assessment for the Patuca River, Honduras:
Maintaining ecological health below the proposed Patuca III Hydroelectric Project

December 15, 2007

Developed by The Nature Conservancy for the Empresa Nacional de Energía Eléctrica (ENEE) of Honduras

This report was the result of a collaborative effort between a number of staff from The Nature Conservancy representing a variety of organizational perspectives (Jeff Opperman, Julio Carcamo, Nicole Silk, and Brian Richter), staff from ENEE, as well as outside experts from Honduras, Central America and the United States. Jorge Jiménez (Organization for Tropical Studies) and Elizabeth Anderson (Global Water for Sustainability Program) helped facilitate the first workshop and Eloise Kendy, Rebecca Tharme and Andy Warner of The Nature Conservancy provided constructive reviews of this report. We are particularly grateful for the significant contributions from Peter Esselman, contractor to The Nature Conservancy, and engagement from the indigenous community along the Patuca River. This product and the extensive exchanges and interactions it represents would not have been possible without the significant financial and personnel contributions from both The Nature Conservancy and ENEE.

Executive Summary

The Empresa Nacional de Energía Eléctrica (ENEE) of Honduras requested that The Nature Conservancy (TNC) conduct an environmental flow assessment for the Patuca River below a proposed hydroelectric project, referred to as Patuca III. The Patuca River is the longest river in Honduras, third longest in Central America, and is currently undammed. The river supports globally important aquatic biodiversity and flows through a reserve for indigenous communities and other protected areas. Communities within these reserves rely heavily on the river for water and transport and as an important source of fish protein. Additionally, the river fertilizes agricultural fields by depositing nutrient-rich sediments on the fields during floods. Due to the Patuca River's important biological and cultural values, ENEE sought information on how the proposed dam may affect the river and its resources and asked TNC for guidance for a managed flow regime that will minimize the impacts of Patuca III on the river's ecological integrity and resources.

An environmental flow assessment was conducted based on a variety of information sources, including field trips along the river, scientific data and expertise derived from similar river systems, analysis of hydrological data, and traditional ecological knowledge. These information sources were synthesized and presented during two workshops. During the workshops, participants from the communities, ENEE, government agencies, non-governmental organizations and academia worked to define collaboratively ecologically and socially important river processes and associated environmental flow recommendations.

This report describes the environmental flow assessment for the Patuca River. Following five background sections, the details of the flow assessment are presented in Section 6, with three sub-sections. Section 6.1 describes the recommended Environmental Flow Components (EFCs)—which include low flows, high-flow pulses, and floods — for normal, wet, and dry years. The EFCs are described in terms of magnitude, frequency, duration, and season (for more detail on the EFCs see "Overview of Environmental Flow Assessment" within this Executive Summary and the main report). The EFCs and hydrological year types (wet, dry, normal) reflect the natural intra-and inter-annual hydrological variability of the Patuca River. In addition, this section describes the linkages between EFCs and important physical and biological processes in the river, such as sediment transport and fish migration. ***These linkages are framed as hypotheses to be tested and refined through further monitoring and research on the Patuca River.*** Future research and monitoring should target the research questions and uncertainties identified through this process to optimize and refine the flow recommendations.

Sinotech, the engineering firm designing Patuca III, provided a data set of daily flow values that simulate releases from the proposed dam based on a 29-year record of Patuca River hydrology. Note that this modeled data set (hereafter referred to as 'with-dam' hydrology) was developed prior to the environmental flow assessment and therefore represents simulated 'status-quo' dam operations that do not incorporate the information from this assessment. Based on the simulated 'with-dam' hydrology several of the recommended EFCs can occur without any intentional release from the dam (i.e., projected status quo operations will provide these EFCs). Patuca III can provide for several of the EFCs through status-quo operations because the dam is projected to be operated as a ‘run-of-river’ facility for much of each wet season. Because floods and late wet-season high-flow pulses tend to occur during this period of ‘run-of-river’ operations, projected status-quo operation of Patuca III appears likely to not affect these EFCs and dam operators will likely not need to intentionally release such flows.

In contrast, mid wet-season high-flow pulses are predicted to be somewhat affected by dam operations and early wet-season high-flow pulses will be greatly reduced in frequency. Based on a thirty-year record of natural (without dam) hydrology, at least two early wet-season pulses occurred in 83% of the years, whereas the with-dam hydrology projects that in only 17% of years will there be two or more early wet-season pulses. These early wet-season pulses provide important cues that influence the migration and reproduction of multiple fish species that are critical for river ecosystems and human communities.

Finally, the projected low-flow values with the dam in place are higher than the recommended low flows for several months, particularly in dry-season months such as April and May. Dry-season low flows exhibit substantial inter- and intra-annual variability under natural conditions but ‘with-dam’ hydrology is projected to provide low flows that are fairly constant throughout the dry season and between years.

Section 6.2 translates the EFC recommendations into basic operational guidance. Here we provide an example of simple rules that reservoir operators can follow to achieve the EFC recommendations. We then provide several scenarios that illustrate the expected flows downstream of the dam that would result from implementing these rules, using actual hydrological data. For example, we use hydrology from 1985, the second driest year in the 29-year hydrological record, to compare simulated ‘status-quo’ dam operations, which would release no high-flow pulses during the early and middle parts of the wet season, to a scenario in which four high-flow pulses are released (2 early, 2 middle of wet season) with durations and magnitudes as recommended by workshop participants. The scenario that released the recommended EFCs would have delayed reservoir refilling by only 2 – 8 days. These scenarios clearly demonstrate that the recommended number of high-flow pulses can be released by the dam in nearly all years (28 out of the 29 years examined) with minimal impact to dam operations.

These scenarios are based on simple rules that may not reflect the planning approach that the dam operators will use or need for reliably predicting power and revenue generation. However, because the scenarios demonstrate that flow recommendations can be released with minimal impacts to reservoir levels and refilling rates, they suggest that more robust and appropriate guidance and rules can be developed that will allow environmental flows to be released in a manner consistent with likely reservoir management objectives. Developing these rules will allow the environmental flow recommendations in this report to become actual flow releases allocated to benefit downstream ecosystems and human communities, and released in a manner that provides sufficient certainty for dam operators and water resource managers.

Section 6.3 describes the effects of hydropeaking, defined as significant daily fluctuations in reservoir releases due to intervals of high releases for power generation followed by much lower releases between intervals of power generation. It is understood that Patuca III will not (or only rarely) be operated for hydropeaking. This is an important consideration, because of the significant negative impacts such peaking can have on downstream river ecosystems and human communities. Because hydropeaking is a very common feature of many hydropower projects, some information on peaking is included in this report as general guidance, should peaking operation occur.

Finally, the ability to release environmental flows is strongly influenced by dam design. This report focuses on an environmental flow assessment; an analysis of the dam's design is beyond the scope of the assessment. However, it is important to note that various aspects of project design can either hinder or facilitate implementation of environmental flows. When working with a project that has already been constructed, design limitations are difficult to address. However, because Patuca III is still in the design phase, there is opportunity to ensure that aspects of dam design will not hinder implementation of important environmental flow releases.

Overview of Environmental Flow Assessment, Patuca River

This section provides a concise summary of the environmental flow assessment conducted by The Nature Conservancy for the Rio Patuca downstream of the proposed Piedras Amarillas Hydropower Project (Patuca III). The first section describes the Environmental Flow Components (EFCs), which are the most important types of flows for maintaining riverine processes. The final report includes detailed descriptions of the relationships between each of the EFCs and important riverine processes. Below we provide the basic information for each EFC, including magnitude, frequency, duration, and season. The characteristics of the EFCs vary for dry, normal, and wet years. The second section provides initial guidance on how these EFCs could be incorporated into operation of the project, although it is anticipated that further analysis could improve the utility and accuracy of such guidance.

1. Environmental Flow Components

Low flows (or base flows)

	Year type		
Month	**Dry (cms)**	**Normal (cms)**	**Wet (cms)**
January	40 – 50	50 – 65	65 – 80
February	30 – 35	35 – 50	55 – 65
March	20 – 30	30 – 40	40 – 45
April	20 – 30	20 – 30	25 – 30
May	20 – 30	20 – 30	30 – 35
June	30 - 35	35 – 60	70 – 90
July	45 – 55	60 – 90	125 – 135
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

Early wet-season high-flow pulses

	Year Type		
	Dry	**Normal**	**Wet**
Time Period	June 1 – July 15	June 1 – July 15	June 1 – July 15
Frequency (events per year)	1	≥ 2	≥ 2
Magnitude Range (cms)	125 - 170	125 – 300	125 - 500
Duration (days)	4 - 10	4 – 10	4 - 10

Mid wet-season high-flow pulses

	Year Type		
	Dry	**Normal**	**Wet**
Time Period	July 16 – November 01	July 16 – November 01	July 16 – November 01
Frequency (events per year)	≥ 4	≥ 4	≥ 4
Magnitude Range (cms)	200 – 600	200 – 900	200 – 900
Duration (days)	4 - 10	4 - 10	4 - 10

Late wet-season high-flow pulses

	Year Type		
	Dry	**Normal**	**Wet**
Time Period	November 1 – December 15	November 1 – December 15	November 1 – December 15
Frequency (events per year)	1	2	2
Magnitude Range (cms)	125 - 170	125 – 300	150 – 350
Duration (days)	4 - 10	4 - 10	4 - 10

Floods

	Year Type		
	Dry	**Normal**	**Wet**
Time Period		August 15 – October 30	August 15 – October 30
Frequency (events per year)	0	≥ 1	≥ 1
Magnitude Range (cms)		1000 - 2000	2000 – 3500
Duration (days)		15 - 40	15 - 40

2. Operational Guidance

Low flows
Proposed dam-released daily average dry-season low flows are anticipated to be considerably elevated above natural flow levels, particularly in April and May. Dam managers should develop operating rules that allow the river to: (1) retain inter- and intra-annual variability; and (2) approach natural low flow values, with consideration for transportation needs (e.g., ensuring flows > 30 cms during important navigation times). Dam releases that are based on a *percentage of inflow* would allow flows to retain more inter- and intra-annual variability.

Early and mid wet-season high-flow pulses

A comparison of natural hydrology with proposed with-dam hydrology indicates that early and mid wet-season high-flow pulses are the EFCs that will be most affected by the initially proposed operations of Patuca III. However, a simple modeling exercise suggests that these EFCs can be released from the dam in nearly every year without appreciably affecting reservoir refilling and hydropower operations. Again, relatively simple operating rules based on a *percentage of inflow* should allow these EFCs to be released and for the river to retain a natural level of inter- and intra-annual variability. Operating rules could be further refined to include consideration of reservoir levels. For example, when reservoir levels are low, a smaller percentage of a high-flow pulse that enters the reservoir could be released; as reservoir levels rise a higher percentage of inflow pulses could be released.

Late wet-season high-flow pulses and floods

A comparison of natural hydrology with proposed with-dam hydrology indicates that late wet-season high-flow pulses and floods will not be affected by the initially proposed operations of Patuca III. These events either occur when the reservoir is already full and the dam is being operated as a run-of-river project (inflow = outflow) or, in the case of floods, the event will quickly fill the reservoir and subsequent releases equal inflow. Therefore, under the initially proposed operations of Patuca III, dam operators will not need to specifically manage for these EFCs.

Environmental Flow Assessment for the Patuca River

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1. Introduction

The Empresa Nacional de Energía Eléctrica (ENEE) of Honduras requested that The Nature Conservancy (TNC) conduct an environmental flow assessment for the Patuca River below a proposed hydroelectric dam, referred to as Patuca III. The Patuca River is the longest river in Honduras, third longest in Central America, and is currently undammed. The river supports globally important aquatic biodiversity and flows through two reserves for indigenous communities and a national park. Communities within these reserves rely heavily on the river for water and transport and as an important source of fish protein. Additionally, the river fertilizes agricultural fields by depositing nutrient-rich sediments on the fields during floods. Due to the Patuca's important biological and cultural values, ENEE seeks information on how the proposed dam may affect the river and its resources and asked TNC for guidance on a flow regime that will minimize the impacts to these resources.

1.1 Constraints and sources of information

Very little information was available for the Patuca River from sources such as scientific journal articles, agency reports, or other sources of data. Further, there was relatively little time to collect new information to inform the environmental review process. Due to this lack of information and short timeframe, ENEE conducted two field trips down the river and held two workshops, the first in December 2006, attended by agency staff, NGOs including TNC, and local university scientists, and the second in August 2007, attended by representatives of communities of the lower Patuca River, along with TNC and ENEE staff. Because very little scientific information was available, and due to the high sociocultural importance of the river ecosystem to local communities, this process relied heavily on Traditional Ecological Knowledge (TEK)—that is, information generated by those who live and work on the Patuca. The second workshop and both the field trips were expressly designed to collect TEK.

This report presents an environmental flow assessment for the Patuca River, synthesized from a variety of sources, including:

1. Traditional Ecological Knowledge
2. Data collected during two field trips
3. Hydrological analysis of flow data, including a comparison of historic unregulated flows (natural hydrology) and modeled flows with the hydroelectric dam operating (with-dam hydrology; note that this modeled data set was developed prior to the environmental flow assessment and therefore represents simulated 'status-quo' dam operations that do not incorporate the information from this assessment)
4. Relevant research from other river systems of same ecotype
5. Outcomes of the two flow assessment workshops

1.2 Report Layout

This report contains five background sections that describe the Patuca watershed, the proposed dam, the field trips, methods for collecting TEK, hydrological analysis, and the workshops. Following these, Section 6 of the report contains the primary environmental flow assessment, organized into three sub-sections. Section 6.1 describes in detail the recommended Environmental Flow Components (EFCs), composed of low flows, high-flow pulses, and floods. Each EFC is defined in terms of magnitude, duration, season and frequency and is accompanied by descriptions of the linkage between the EFC and specific river processes. For example, floods are associated with sediment transport and early wet-season high-flow pulses are associated with fish migration patterns.

Section 6.2 provides practical guidance on how dam operators can implement the recommended EFCs. This guidance consists of relatively simple rules for dam management and uses scenarios based on actual hydrological data to illustrate the implications of the proposed environmental flow releases on reservoir management.

Section 6.3 emphasizes the effects of hydropeaking on river ecosystems. Although it is understood that Patuca III will not be, or only rarely will be, operated for peaking, this section is provided as general guidance on reservoir operation because peaking is a common feature of many hydropower projects.

In addition to this report describing the environmental flow recommendations, The Nature Conservancy (TNC) has conducted analyses of the hydrologic implications of Patuca III, participated in the first field trip, contributed to the design of the two environmental flow workshops, and provided initial assessments of ecological and social concerns due to the proposed changes. These earlier efforts are captured partially by the following documents: (1) Preliminary Indicators of Hydrologic Alteration Analysis for the Patuca River by Jeff Opperman (an analysis of the hydrological alterations likely under a predicted dam-influenced flow regime, using the *Indicators of Hydrologic Alteration* software); and (2) Ecological and Social Impressions of the Middle Patuca River and Potential Consequences of the Patuca 3 Hydropower Project by Peter Esselman (a description of the September 2006 field trip on the Patuca River including information on the life histories of various fish species and conceptual models of Patuca River ecosystems); and (3) Summary report of the first workshop (November, 2006). These documents are also included as appendices to this report.

2. Background

The relationship between TNC and ENEE pertaining to the Patuca River and the Patuca III project is described by the Memorandum of Understanding executed by TNC and ENEE in September, 2006 (Appendix 1). As stated by that document, whatever recommendations that emerge as a result of this process and collaboration will be ENEE's product exclusively. TNC is not a sponsor, convener, facilitator or other term indicating full or partial proprietary control over this process or associated products. The Nature Conservancy's contributions to this project are part of its agreement to provide ENEE with exposure to practices and approaches relevant to ecologically sustainable water management so that ENEE can develop appropriate environmental flow recommendations to influence the design and be incorporated into the operation of the Patuca III project.

2.1 The River and Watershed

The Patuca River is currently undammed and is the longest river in Honduras and the third longest river in Central America (Figures 1 and 2). The name "Patuca" is given to the river formed by the confluence of the Guayape and Guayambre Rivers and, from that junction, the Patuca flows 465 km to the Caribbean Sea. The total drainage area of the Patuca River is approximately 2.4 million ha. The mean annual flow (MAF) of the Patuca River at Cayetano, just downstream of the proposed site for Patuca III, is 135 cubic meters per second (cms); the MAF at Kurpha, after nearly all the major tributaries have entered, is 429 cms.

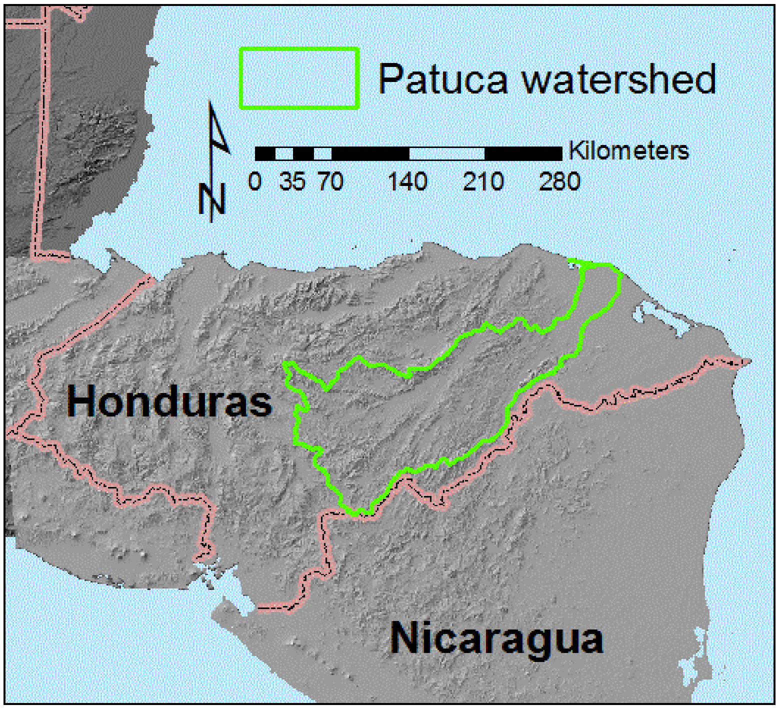

Figure 1. The Patuca River watershed within Honduras.

Land use in the upper watershed consists largely of cattle ranching and extensive areas of forest have been cleared for pasture. The lower watershed is more heavily forested with extremely low road density. The lower river flows through three large reserves: Patuca National Park, The Tawahka Biosphere Reserve and the Rio Platano Biosphere Reserve (Figure 2).

The aquatic biodiversity of the Patuca River has only been documented in the estuarine portion of the river near where it meets the sea. Large-scale surveys of freshwater riverine habitats in Honduras indicate high levels of endemism in the larger river basins (i.e. species found nowhere else; Wilfredo Matamoros, University of Southern Mississippi, personal communication). This trend suggests that intensive sampling of the Patuca River will also probably reveal multiple species endemic to the river system.

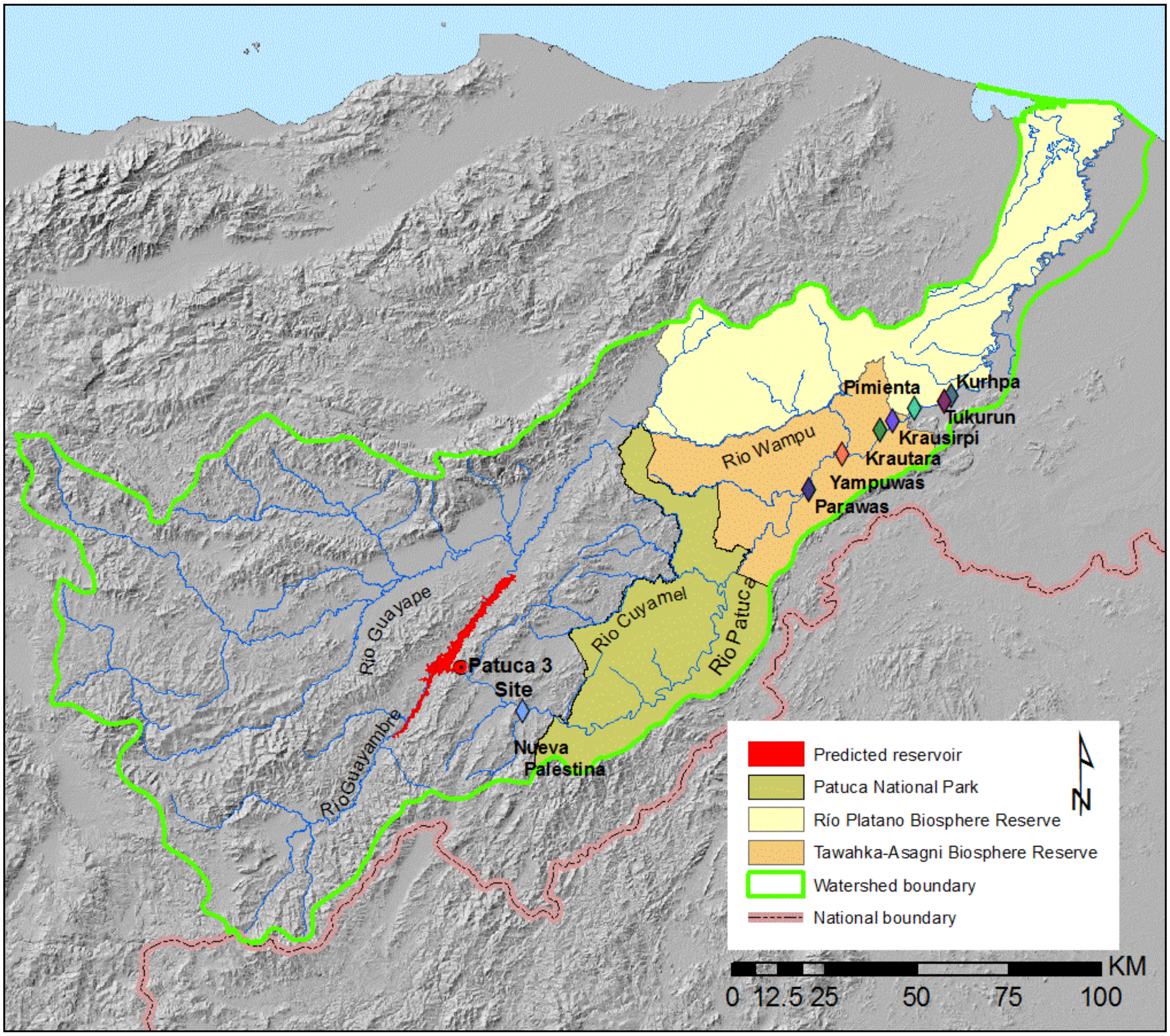

Figure 2. The Patuca River watershed with protected areas and communities along the river. The proposed reservoir is indicated in red at the confluence of the Guayape and Guayambre rivers.

<u>2.2 Communities of the Patuca River</u>

Numerous communities are located along the banks of the Patuca River (Figure 2). The lower reaches are populated by three primary ethnic groups: Tawahkan, Miskito, and Pech. Other communities consisting of more recent ladino settlers also occur along the river. The indigenous communities traditionally depend on the river for numerous benefits. The river is a source of drinking water and provides the primary mode of transport between communities and for trade. The river supports several sources of food, including fish and reptiles (meat and eggs). Finally, the river provides a source of nutrient-rich sediment that fertilizes and replenishes low-lying agricultural fields during floods.

2.3 The proposed dam

The currently proposed dam site (Piedras Amarillas) was first identified and investigated in 1975 by Harza Engineering and identified as feasible in 1998 by Geracon/RSW International, Inc. In October 2006 ENEE signed a Memorandum of Understanding with Taipower for designing and constructing the proposed dam. Taipower hired the engineering firm Sinotech to complete feasibility studies and design the project.

The proposed dam will be located on the Patuca River 5 km below the confluence of the Guayambre and Guayape rivers (Figure 2). The drainage area above this site is 1.2 million ha, or approximately half of the overall Patuca watershed. The proposed reservoir will occupy an area of 72 km^2 (7200 ha) with a volume of 1,200 million cubic meters (Mcm). The dam will have a height of 60 m with a crest length of 208 m.

The proposed design for the power plant includes two turbines and a total generator capacity of 104 MW. The turbines are sized for maximum discharge of 135 cms each and a single turbine cannot operate below 40 cms.

3. Hydrological Analysis

Discharge in the Patuca River exhibits considerable intra-annual variability with a strong seasonal pattern (Figure 3). The dry season occurs between January and May with low and relatively constant flows. May and June are transitional months between the dry season and the wet season, with storms leading to high-flow pulses. The wet season lasts from July to December and can include very large storms and floods. Patuca River hydrology also displays considerable inter-annual variability with individual years that range from very dry to very wet (Figure 4).

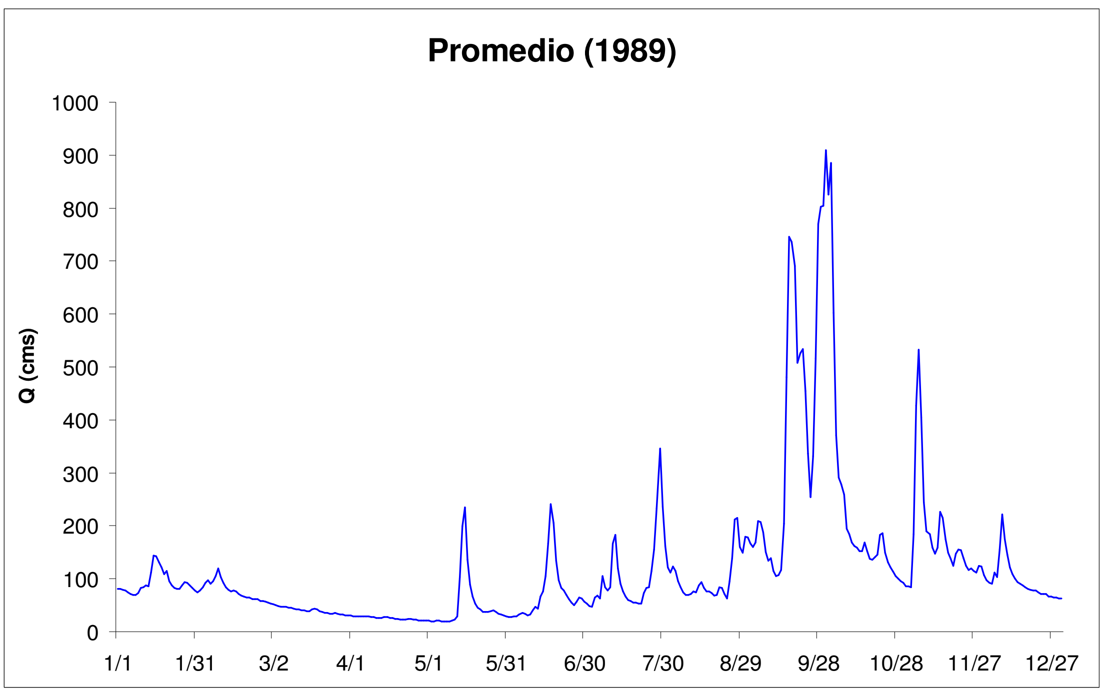

Figure 3. Hydrology of the Patuca River at the Cayetano gauge for 1989.

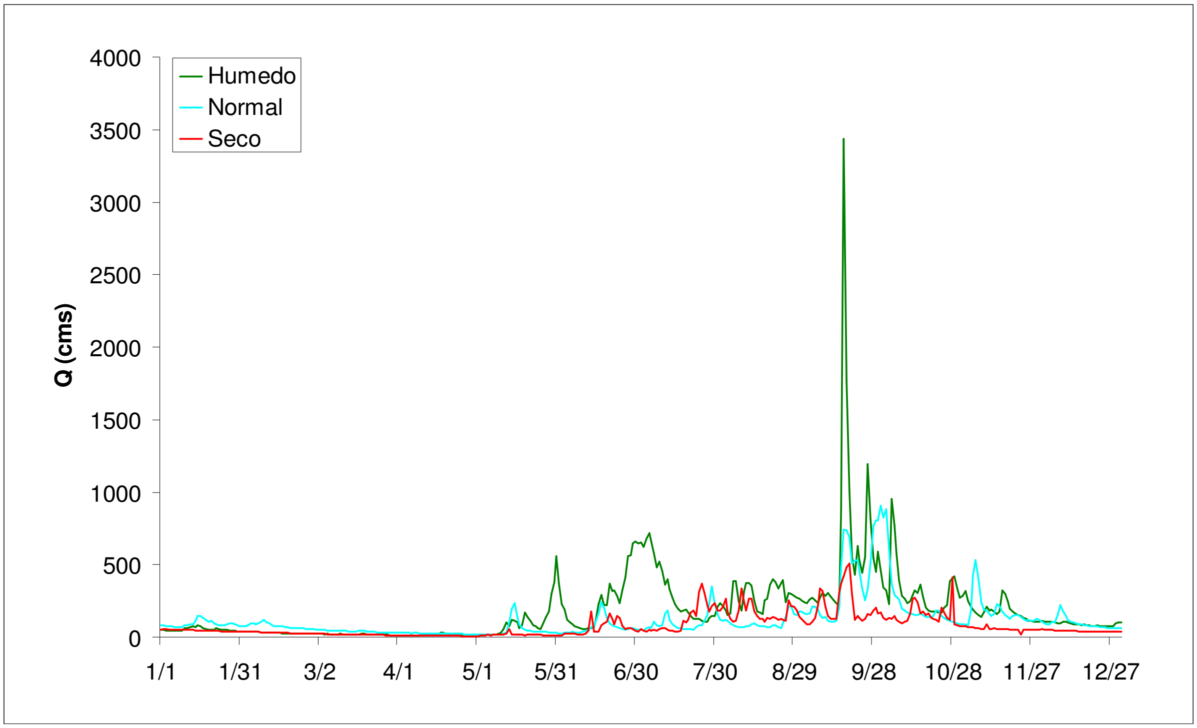

Figure 4. Hydrology for the Patuca River showing years which are wet (humedo), dry (seco), and normal.

The Nature Conservancy used the *Indicators of Hydrologic Alteration* (IHA) software to investigate potential changes to the hydrological regime from dam operations. Sinotech and ENEE provided TNC with hydrological data for Cayetano, a short distance downstream of the proposed dam site, including 29 years of gauged daily flow data and simulated with-dam flows for the same time period (1973-2001). Corresponding data were also provided for a gauge near Kurpha. The results of these analyses are found in the report "Preliminary Indicators of Hydrologic Alteration Analysis for the Patuca River" (see Appendix 2)**;** the most important concepts are briefly summarized below.

3.1 Cayetano gauging station

The IHA analysis for Cayetano indicated that the greatest hydrological alterations with dam operations will be: (1) elevated low flows during the dry season (February – May; Figures 5 and 6) and (2) a decline of high-flow pulses during the wet season from an average of 10 per year to 5 per year (Figure 7). Review of natural and with-dam 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). The analysis indicated that floods will be essentially unchanged with dam operations.

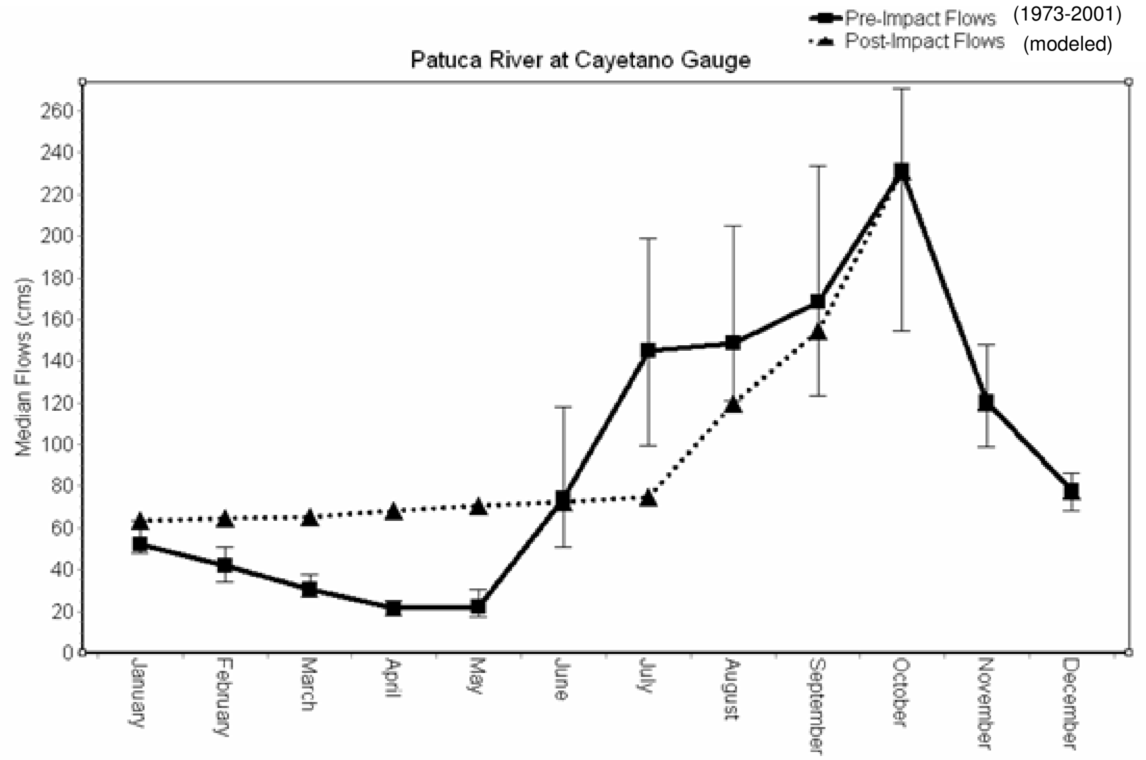

Figure 5. Median monthly flows for the Patuca River comparing natural (black line and squares) and modeled with-dam (dashed line with triangles) hydrology.

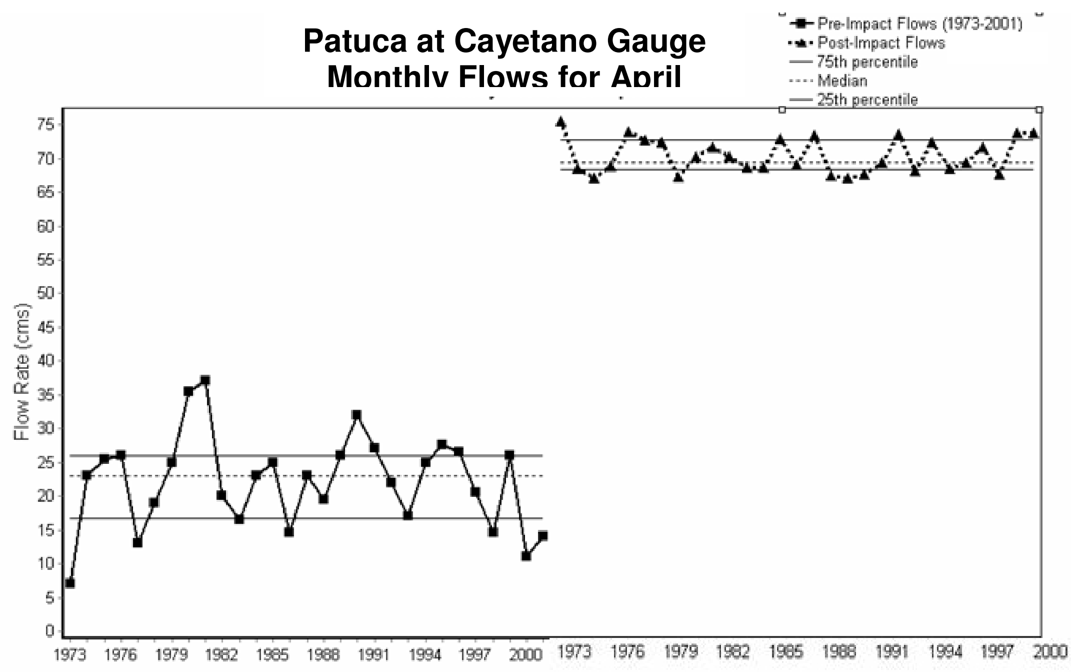

Figure 6. Monthly median discharges for April for the Patuca River at the Cayetano gauging station, comparing natural (black line and squares) and modeled with-dam (dashed line with triangles) hydrology (1973 – 2001).

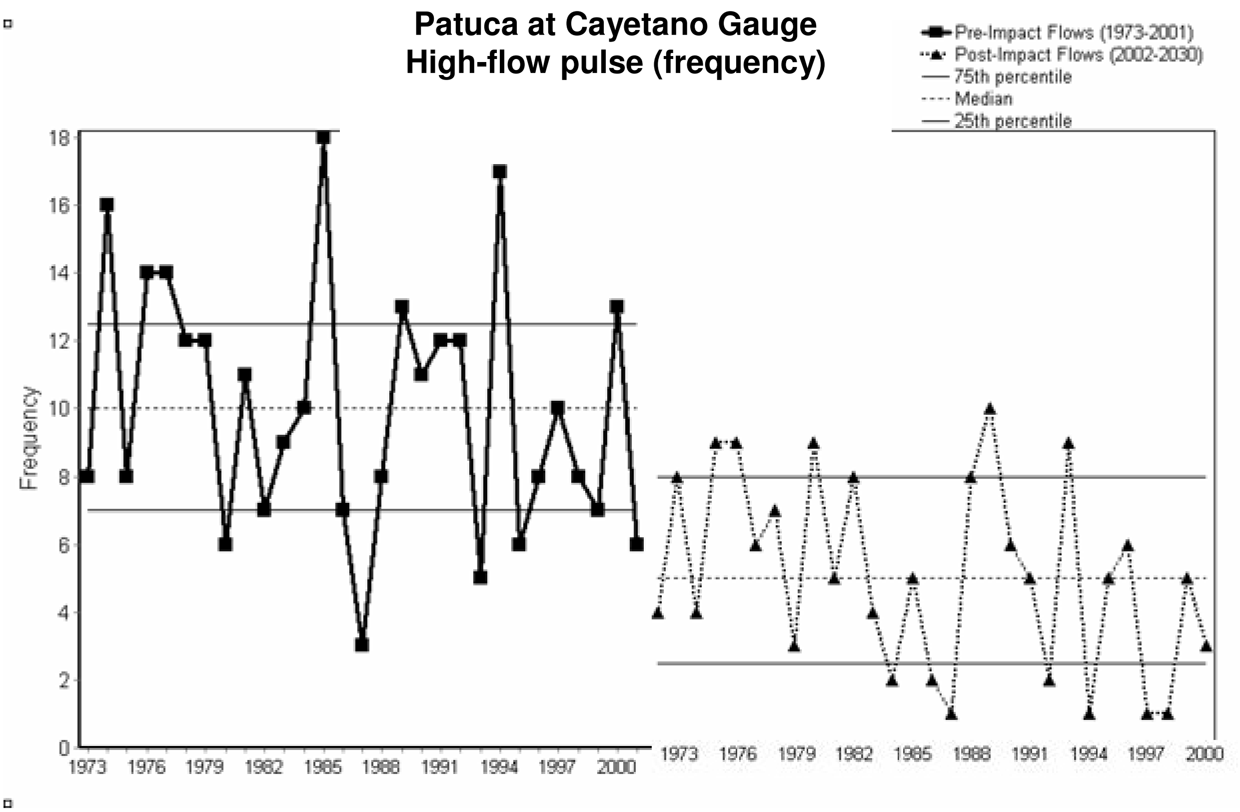

Figure 7. Frequency of high flow pulses (# of pulses per year) for the Patuca River at the Cayateno gauging station, comparing natural (black line and squares) and simulated with-dam (dashed line with triangles) hydrology

3.2 Kurpha gauging station

Over a 29-year hydrological record, approximately one-third of the annual discharge at Kurpha was derived from the portion of the watershed above Cayetano (i.e., the portion of the drainage area above the proposed dam; Table 1). In only the months of June and July did more than half of the flow at Kurpha derive from above the dam site; for most months the proportion was approximately 20%. The IHA analysis indicated that the primary hydrological alteration likely at Kurpha is an increase in low flows during the dry season.

Table 1. Monthly flows and mean annual flow (MAF; in cms) for the Cayetano and Kurpha gauges. "Proportion' indicates the proportion of the flow at Kurpha represented by the flow at Cayetano over a 29 year hydrological record (1973-2001).

	Cayateno	Kurpha	Proportion
January	60	285	0.21
February	47	232.5	0.20
March	34	168	0.20
April	23	124.5	0.18
May	23	95	0.24
June	70	104	0.67
July	145	203	0.71
August	180	465	0.39
September	207	603	0.34
October	232	683	0.34
November	120	545	0.22
December	82	421	0.19
MAF	135	429	0.31

4. Field trips

To provide new information on the Patuca River, two field trips were conducted down the river. The first field trip occurred in August and September, 2006 (a period of relatively high base flows) and the second occurred during May, 2007 (a period of low base flows).

During the first field trip, a group of 12 researchers visited 11 communities (Mestizo, Tawahka, and Miskito) while traveling 250 km along the river in a dugout canoe (Figure 8). Kurpha was the most downstream community visited on the field trip and Nueva Palestina was the most upstream community visited (Figure 2). The 12 people were divided into 4 teams: a survey team that took cross section information at 12 points along our route; a water chemistry team that collected data at 18 points along our route; a social/geomorphology interview team; and a fishes/ecosystems interview team.

The survey team used rod and transit to survey the morphology of channel cross sections up to the levels of reasonable flood magnitude. Along with the cross sectional information, a forester characterized vegetative communities in the floodplain area of these transects, and a soils expert characterized soils and land use. The water chemistry team recorded dissolved oxygen, secchi depth, electrical conductivity, pH, and temperature at both banks of 18 points on the river, including all of those where transects were surveyed.

Two teams conducted interviews with community members: one focused on fish and ecosystems, the other on sociology and geomorphology. Sociology and geomorphology were grouped together because the social team was interviewing village elders with a long-term perspective on patterns of river geomorphology. The sociology and geomorphology team used two questionnaires, one devised by ENEE, and one devised by TNC for questions about river geomorphology. The fishes/ecosystems team sought out the individuals with the most experience capturing fishes and aquatic animals (Figure 9) and conducted 16 interviews with a total of 29 community members. This team used a questionnaire developed by TNC along with laminated pictures of fishes thought to occur in the Patuca watershed. The fishes/ecosystems interview questions focused on detailing the composition and biology of aquatic assemblages with special focus on fishes.

More information on the methods and results of this field trip can be found in ENEE reports and in a report written by Peter Esselman (see Appendix 3).

Figure 8. Field trip down the Patuca River.

Figure 9. Interviewing community members about important fish species.

The second field trip occurred in mid-May, 2007. Details of this field trip can be found in ENEE reports. Community members were given paper and crayons or color markers and were asked to pictorially illustrate their communities, their crops, and the river during different times of the year (Figures 10 and 11).

Figure 10. Community members drew maps of the river, agricultural fields, and their towns.

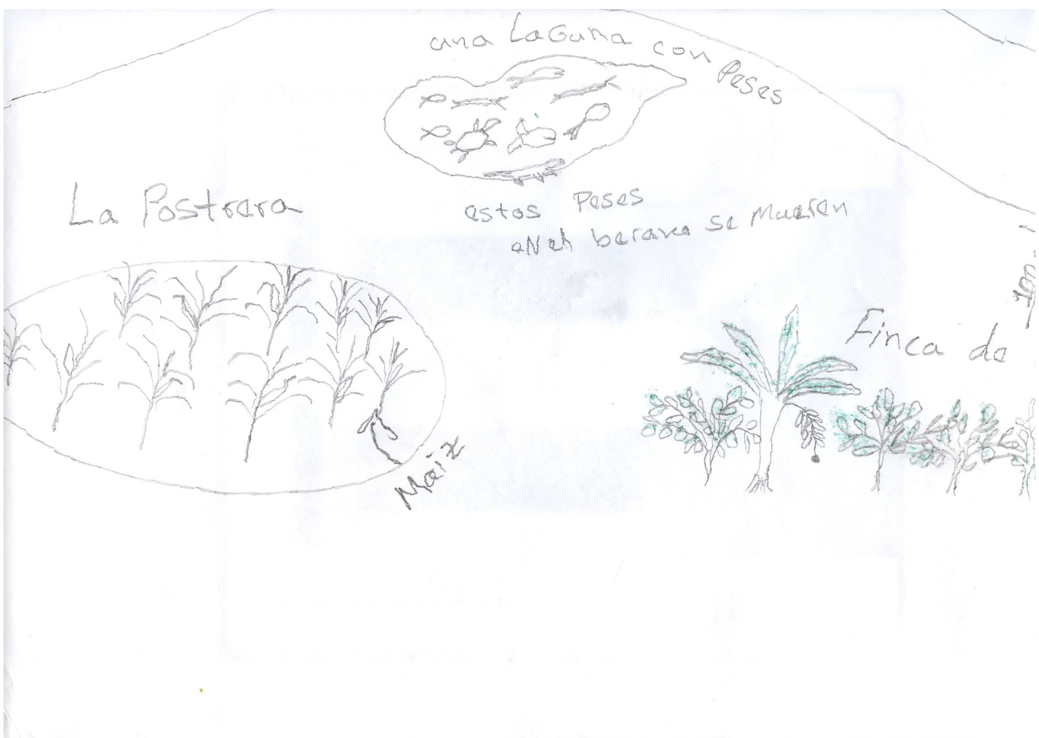

Figure 11. An example of a map of the river and fields drawn by community members.

5. Environmental Flow Workshops

5.1 First workshop - Tegucigalpa, November 29-30, 2006

The purpose of the first workshop was to bring scientists, engineers, and water managers together to consider how the Patuca ecosystem functions ecologically and hydrologically and to develop a unified recommendation of the flows necessary to sustain the ecological health of this system so that it can support both biodiversity and humans.

The workshop began with presentations providing context to participants regarding the resources of the Patuca River: ENEE staff and others gave presentations on the Patuca River and its resources, and the proposed dam; TNC staff and others described the importance of a river's flow regime to riverine processes and ecosystems and presented a process for developing environmental flow recommendations. Following the presentations, workshop participants divided into three working groups focused on: (1) fish and other aquatic organisms (referred to as the 'peces' group); (2) terrestrial resources, including human communities (the 'terrestres' group); and (3) channel morphology ('forma'). Each working group developed its own set of hydrological recommendations for the components of concern. The three groups' recommendations were synthesized into a draft set of proposed environmental flow recommendations and this was given to ENEE for comment. (The working groups' notes, hydrological recommendations and other information about the workshop are summarized in the report "Patuca River Environmental Flows Workshop Summary Report," and are included here as Appendix 4).

5.2 Second workshop – Tegucigalpa, August 8 and 9, 2007

The second environmental flow assessment workshop was focused on incorporating indigenous community members' knowledge about the river. Twelve individuals, representing Tawahka and Miskito communities, attended the workshop. The workshop was also attended by several employees of TNC and ENEE and Wang Chung-Fu, an engineer from Sinotech. The morning of the first day of the workshop included several presentations about the river, the proposed hydroelectric project, and information collected during the field trips.

During the afternoon, workshop participants divided into three groups focused on agriculture, fisheries, and transportation. During these breakout groups, community members identified river processes and conditions that were associated with either desired benefits or difficulties. Several methods were used to identify flow levels that they considered beneficial or desirable for their livelihoods, riverine biota, and transportation at different times of year, and those that were detrimental. For example, both the fisheries and agriculture groups annotated photos to show the river stages associated with important river conditions (Figures 12 and 13). The agriculture group also drew a map of one of the communities and its agricultural fields and drew lines corresponding to common flow levels during different seasons (Figure 14). The transportation group drew a map of the river and identified the most challenging areas for boat traffic (Figure 15). Community members also identified recent months where flow conditions were appropriate for a desired use of the river so that the flow levels associated with those dates could be identified. For example, through this process the transportation group identified that 30 cms was a low flow level that was still compatible with transportation.

More information on the discussion from the second workshop can found in the ENEE report, "Resumen Mesas de Trabajo Taller Agosto de 2007."

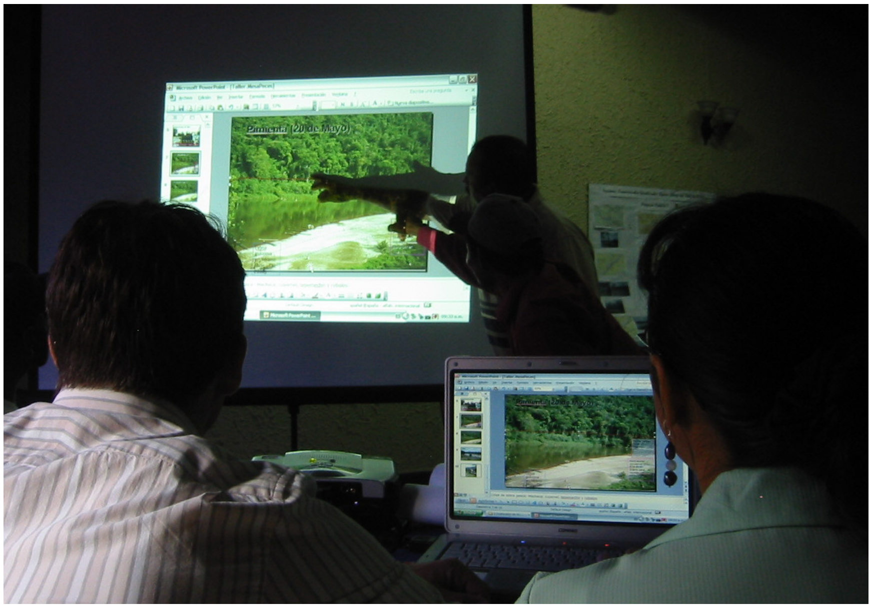

Figure 12. In the background of this photo, a fisherman describes flow levels and identifies the stage associated with that flow level on a photo of the Patuca River. In the foreground, workshop facilitators draw a line corresponding to that river stage on the photo on the computer.

Figure 13. A photo of the Patuca River at Krausirpi annotated by community members to indicate river stages at various months. The point bar in the upper left is a mix of forest and agriculture.

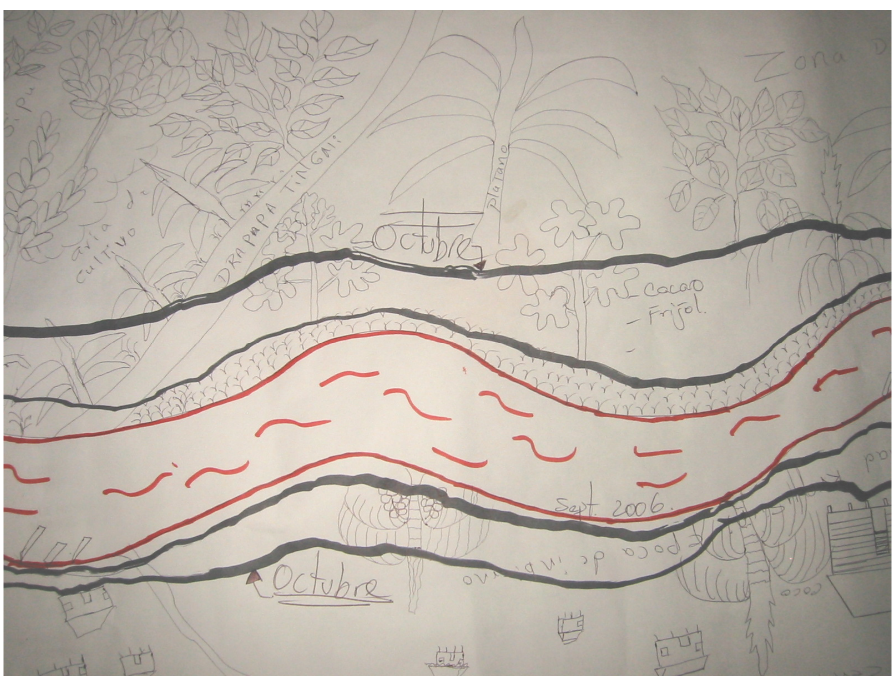

Figure 14. A community map drawn during the second workshop.

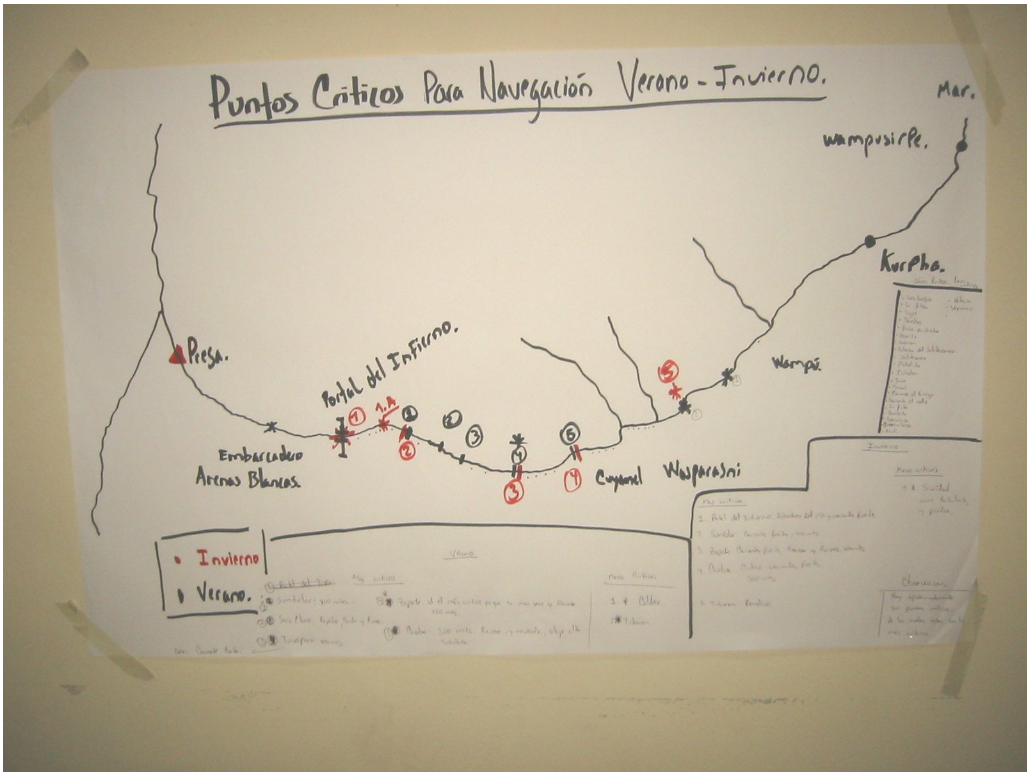

Figure 15. A map of the Patuca River below the proposed dam sites indicating areas that pose challenges to navigation.

6. Environmental Flow Assessment

Guidance on environmental flows is contained within the following three sub-sections. Section 6.1 describes the recommended Environmental Flow Components (EFCs) which include low flows, high-flow pulses, and floods. The recommended EFCs are described in terms of magnitude, frequency, duration, and season and are organized by normal, wet, and dry year types. The EFCs provide guidance on the important types of flows and flow variability within a year, while the year types account for variability between years (Figures 3 and 4). Section 6.2, 'Operational Guidance,' describes a simple approach for implementing the recommended EFCs in most years. Although Section 6.2 may prove most useful for guiding actual operations, it should be considered in conjunction with Section 6.1, which contains important background information on the importance of specific EFCs and describes the linkages between EFCs and river structure and processes.

6.1 Environmental Flow Components

The historical record of daily flow magnitudes available for Cayetano exhibits a range of variability within which several "year types" can be defined. We defined 'dry', 'normal', and 'wet' year types—a central theme around which the final flow recommendations are organized. 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, and wet years were defined as those greater than one standard deviation above, the average annual flow. Using this approach, 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.'

Environmental Flow Components (EFCs) are types of flow with biological or human importance and include low flows, high-flow pulses, and floods**.** EFCs can be defined in terms of season, frequency, magnitude and duration and, in this flow assessment, the recommended values for those characteristics vary by hydrological year type (dry, normal, wet). In general, the rates of change of flows should be within the natural range of variation. More specific guidance on rates of change is provided in the section on hydropeaking (6.3).

Intra- and inter-annual environmental variability are essential parts of a river ecosystem that facilitate the maintenance of biodiversity and ecosystem services important to human communities. Different species and even individuals within a species thrive under different optimal conditions. Species that exist currently within the Patuca River ecosystem are adapted to—and may even benefit from—the intra- and inter-annual range of flow conditions experienced in their environment. At least 14 migratory fish and shrimp species in the Patuca River rely on wet-season high-flow pulses and floods to trigger and facilitate migration (both up and downstream; see Appendix 2 for listing of migratory species). These species are likely to have multiple spawning events annually, with early maturing fish spawning with the early high flows, and, late maturing fish spawning on later floods. A number of non-migratory fishes may experience high-flow conditions as stressful, and would benefit from lower wet-season flows or no floods at all. However, even non-migratory species may benefit from the exchange of nutrients and material between the river and the riparian corridor that occurs during floods. Migratory and non-migratory species can co-exist in part because (1) some years are wet and some years are dry, so over time the optimal requirements of all species are served, (2) in sub-optimal years, these species are adapted to survive well enough until conditions improve for their growth and or survival.

The final recommended flows for Patuca III embrace the concept of a flexible management regime that responds to inter-annual variation in flow availability. By making recommendations for dry, normal, and wet years we attempt to maintain variability in the long-term flow of the river on the assumption that natural variation in flow conditions will help maintain a diverse and healthy ecosystem downstream of the dam. Each EFC is accompanied by a description of its linkage with important riverine physical and ecological processes. It is important to note that the analyses and workshop discussions did not cover *all* components of the ecosystem, and so the linkages described for each EFC do not represent an exhaustive list. The various EFCs are represented in Figure 16.

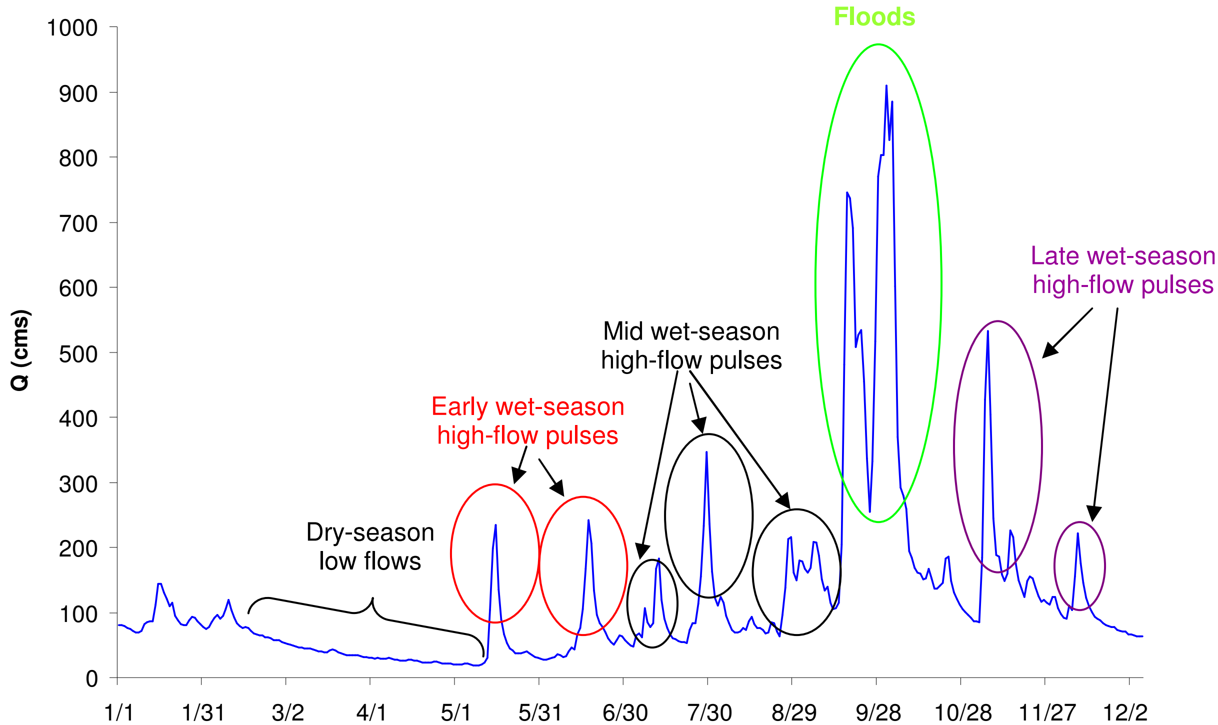

Figure 16. Hydrograph from the Patuca River at the Cayetano Gauge, 1989 with the Environmental Flow Components identified. This is the same hydrograph as found in Figure 3.

6.1.1 Low flows

Like other rivers in the seasonal neotropics, the Patuca River has a predictable and more-or-less consistent period of very low flows from January through May, after which river flows become more variable as high-flow pulses begin to interrupt the steady base flows. This low-flow period should be considered a crucial aspect of the natural flow regime of the Patuca River to which many ecosystem components and human communities are adapted.

Dry-season low flows within their natural range of variation are important for many reasons identified during the workshops and other analyses.

- At least nine resident, non-migratory fishes in the cichlid family—including the 'tuba' (*Vieja maculicauda*), one of the main species eaten by people along the river—nest and reproduce during dry-season low flows. These species depend upon stable flow conditions, clear water (for mate location and competition), and possibly other environmental cues (higher temperatures, higher electrical conductivities) that signal reproduction.
- Several important reptiles require sandy beaches exposed during low water conditions for their reproduction. These include green iguanas, at least five species of freshwater turtles, and crocodiles. These reptiles represent important top predators in the riverine food web and also provide food to the communities (meat and eggs).
- The clear waters and low water levels lead to conditions where nutrients are concentrated in the river and sunlight penetrates to the bottom, fueling photosynthesis and increased

food availability for herbivorous fishes (e.g., cuyamel, *Joturus pichardi*) and invertebrates (insects, molluscs, and shrimps).

- Low waters also concentrate fishes leading to increased feeding efficiency and growth of important predatory fish such as snook (blanco, *Centropomus undecimalis*) and wolf cichlid (guapote, *Parachromis dovii*), two species that are important food items for humans. The low clear water also improves the capture efficiency of fishermen.
- Navigation for human populations from the downstream villages to Nueva Palestina and other upstream areas depends upon sufficient water in the river during this period of the year. Water levels that drop too low inflict economic cost in the form of increased travel time and greater risk for engine damage on exposed rocks and snags.

The final recommended dry-season discharges for the Patuca III project were determined by considering the points mentioned above in conjunction with statistics from 29 years of historic flow data. The final recommendation comes in the form of a range of values within which flow releases from Patuca III should fall. Ranges of values were defined by looking at the distribution of monthly low-flow values based on the 29-year period of record. The recommended dry-year values are drawn from a range between the 10^{th} and 25^{th} percentiles of low-flow values; the recommended normal-year values are drawn from a range centered on the 50^{th} percentile of low-flow values; recommended wet-year values are drawn from a range between the 75^{th} and 90^{th} percentile of monthly low flow values. The recommended ranges were adjusted somewhat to account for factors such as navigation. These ranges are shown in the Table 2.

Table 2. Dry-season low flows.

	Year type			
Month	**Dry (cms)**	**Normal (cms)**	**Wet (cms)**	**Example flow-ecology linkages**
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	20 – 30	30 – 40	40 – 45	• Flows below 30 cms make transportation very difficult • Cichlid fish spawning
April	20 – 30	20 – 30	25 – 30	• Cichlid fish spawning
May	20 – 30	20 – 30	30 – 35	• Cichlid fish spawning

Wet-season low flows (or base flows). Wet season (June to December) flows in the Patuca River are characterized by high variability in magnitudes in most years, and the magnitude of low flows is generally more variable. However, low flows in the wet season still have biological and human importance for the following reasons:

- Elevated low flows in the early part of the wet season are likely to serve as a cue for wet-season spawners to prepare for their downstream migrations. Elevated low flows in the late part of the wet season create a freshwater signal in the estuary, providing cues for up-migrating juvenile fishes to begin their movements upstream.
- Wet season navigation is facilitated by higher water levels that allow boats to ascend and descend rapids more easily.

Ranges of wet-season low-flow discharge values were defined in a similar manner as described above for dry season values. These ranges are shown in the Table 3.

Table 3. Wet-season baseflows.

	Year type			
Month	**Dry (cms)**	**Normal (cms)**	**Wet (cms)**	**Example flow-ecology linkages**
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

6.1.2 Early wet-season high-flow pulses

The transition between the dry and wet seasons is a time of much activity within the river ecosystem. Rainfall increase river flow which flushes the channel of stagnant, poor-quality water that accumulates during the low-flow period and triggers many biological events, such as spawning for several species (e.g., 'Pupu', *Poecilia* sp.). Typically in the historic record, the river experiences 1-4 small pulses of high water during the end of the dry season and early part of the wet season (average of 2.5 pulses from 01 June to 15 July). These sporadic but common fluctuations are important for several reasons:

- Predation pressure on young fishes spawned during the dry season is reduced because of increased water volumes, decreased underwater visibility due to higher turbidity, and increased access to the more complex habitats (e.g., banks, bars, side channels, and riparian corridor) made available by rising waters.
- Pulses may provide important cues to migratory fishes to prepare for and/or initiate downstream migrations.
- Many fishes spawn during this time of year so their young can mature during the period of low predator efficiency (because of high water volume and low visibility).
- Tree germination is encouraged by higher water tables, and soil wetness in/near the river banks

- Substrates are cleaned of accumulated sediments and detritus, which may become entrained in the water column and serve as food for downstream drift feeders (e.g., invertebrates like caddis flies, black flies, chironomids, and Atyid shrimps; some fishes).

Table 4. Recommended characteristics of early wet-season high-flow pulses:

Time period: June 1 – July 15
Frequency:
Dry year: 1 event
Normal year: at least 2 events
Wet year: at least 2 events
Magnitude range:
Dry year: 125 – 170 cms
Normal year: 125 – 300 cms
Wet year: 125 - 500 cms
Duration: 4 -10 days

6.1.3 Mid wet-season high-flow pulses

In most years, the wet season is well established by mid July, and after the passage of smaller flow pulses early in the season, larger pulses begin. These pulses can have sufficient power to move and reorganize channel features and material (e.g., sediments, organic matter, sand and gravel bars, and trees) and potentially deposit sediments into the lower areas of the floodplain. Important ecosystem components and services that are affected by mid wet-season high-flow pulses include:

- Pulses of sufficient magnitude likely trigger spawning activity by migratory species. In dry years when no floods typically occur, mid wet-season high-flow pulses take on extra importance because these are the highest flows of the year, and thus are the only flows that may assist down migration of this important species group.
- Young of the year and small-bodied fishes benefit from increased water volumes, lowered visibility, and access to complex bank habitats because they are able to avoid predation.
- Fishes access terrestrial habitats where they may benefit from access to new food resources such as terrestrial invertebrates.
- High water levels deposit nutrient-rich sediments that can benefit crops and riparian ecosystems.

Table 5. Recommended characteristics of mid wet-season high-flow pulses:

Time period: July 16 – November 01
Frequency: At least 4 pulses, regardless of dry, normal, or wet year
Peak magnitude range:
Dry year: 200 – 600 cms
Normal year: 200 – 900 cms
Wet year: 200 – 900 cms
Duration: 4 - 10 days

6.1.4 Floods

Floods are high-magnitude flow events that are recommended for normal and wet years only (the years classified as 'dry' in the 29-year data set did not have floods). Historically, large flood events occurred in the time period between August and October, although events occasionally occurred earlier (June or July) or later (November). As with the other EFCs, the historical hydrological data were consulted to define flood magnitude, frequency, and duration. Floods have the potential to benefit river and human systems, but can also be detrimental to humans at especially high magnitudes. The magnitude of events that cause such damage, particularly to crops and communities, should be investigated. The flood EFCs currently include an arbitrary upper limit that is thought to be below the threshold of damaging floods. However, as currently envisioned, Patuca III will have limited ability to attenuate flood flows and therefore dam managers will not be able to influence whether or not natural floods exceed the EFC threshold.

Floods are crucial components of the natural flow regime to which riverine organisms are adapted. The ecosystem processes supported by a flood include:

- Sediment transport and delivery to flood plains. For farmers downstream, these sediments represent a source of natural fertilizer that enriches their crops with nutrients.
- Sediment and wood movement and re-sorting to create and maintain a diversity of habitats used by river organisms, and to maintain a deep main channel that facilitates navigation.
- Creation of floodplain topography and maintenance of ecosystem heterogeneity.
- Fish are able to access the floodplain and off-channel habitats where productive feeding on terrestrial food sources, and some reproduction, can occur.
- Fish migration to the estuary occurs with the largest floods.
- Tree seed dispersal.

Table 6. Recommended characteristics of floods:

Time period: August 15 – October 30
Number of events:
Normal year: at least 1 event
Wet year: at least 1 event
Peak magnitude range:
Normal year: 1000 - 2000 cms
Wet year: 2000 – 3500 cms
Duration: 15 - 40 days

6.1.5 Late wet-season high-flow pulses

As the wet season begins its transition back to the dry season (Nov. to Dec.), occasional small high-flow pulses occurred fairly regularly in the historical record. These pulses, though not as crucial as some of the larger flows recommended above, still may have importance for habitat creation and migratory species.

- Late wet-season pulses may facilitate the migration and dispersal of young of any late-spawning fishes that do not migrate in the big flood events earlier in the year.
- Migratory fishes spawned in the early part of the wet season begin to seek the river mouth around December, perhaps in relation to a cue caused by freshwater entering the coastal zone. Late wet-season pulses may thus be important for maintaining a freshwater signal in the estuary late into the wet season.
- Small pulses have sufficient strength to move fine sediments like sand, and thus may facilitate the building of beaches that are important for reptiles.

Table 7. Recommended characteristics of late wet-season high-flow pulses:

Time period: November 1 – December 15
Number of events:
Dry year: 1 event
Normal year: 2 events
Wet: 2 events
Magnitude range:
Dry year: 125 - 170 cms
Normal year: 125 – 300 cms
Wet year: 150 – 350 cms
Duration: 4 – 10 days

6.2 Operational Guidance for implementing EFCs

A review of the hydrological record and simulated "with-dam" flow releases suggests two primary challenges for implementing the Environmental Flow Components described above:

1. Although there is a statistically significant correlation between dry-season discharge and annual discharge ($F = 5.6$; $p = 0.02$), there is relatively low predictive power ($r^2 = 0.17$; i.e., dry-season discharge can explain only 17% of the variability of annual discharge and 83% of the variability is due to other factors). Thus it is difficult to predict whether a year is of a 'dry,' 'normal,' or 'wet' type based on the dry-season discharge. Two of the four wettest years had below-average dry-season flows (1995 and 1998). 1998 was the second wettest year overall but had the second driest dry season overall. Conversely, the 10 wettest dry seasons included four years that were ultimately classified as being average or below-average for annual discharge. It will be difficult for dam managers to know whether they are in a 'wet,' 'dry,' or 'normal' year until September, October or November. By this point, however, managers will have needed to have made several decisions about flow levels and pulse releases. Therefore, managers will need an additional framework to guide actual operational decisions.
2. Because the dam will have relatively small storage capacity, in nearly all years the reservoir will fill and begin to operate as 'run of the river' (i.e., outflow = inflow) during the wet season. As a result, many of the recommended EFCs occur at a time of year when it appears that dam managers will not be actively controlling flows. While the dam is operating in a run-of-river mode, the river's natural flow regime will be maintained and many of the recommended EFCs will occur naturally, without any management intervention. It will therefore be helpful to clarify which EFCs tend to occur without management intervention and which will require explicit management attention.

To address these two challenges, this section provides an analysis of which EFCs will likely be met without explicit management of dam releases (i.e., they will occur "naturally"). This section also includes relatively simple rules that will provide guidance on when to intentionally release flows to meet the EFC recommendations, based on current and seasonal hydrology. We then use scenarios based on real hydrological data to show the implications, in terms of reservoir refilling and hydropower operations, of implementing these rules and releasing certain EFCs.

Note that these simple rules should be considered as preliminary examples of operational guidance. First, actual dam operations may differ from the simulated with-dam hydrology that underlies this analysis. Second, these rules are simple and may not reflect the planning approach that the dam operators will use or their need for projecting hydropower generation. TNC expresses its strong interest in remaining engaged in the planning process for Patuca III and to work collaboratively with ENEE and TaiPower to develop more robust and practical rules for implementing the EFCs with minimal effect on dam operation objectives.

6.2.1 Dry-season low flows (January-June)

With-dam daily average flows during the dry season are projected to be much higher than natural dry-season flows (e.g., median natural discharge for April is approximately 25 cms compared to projected with-dam April median discharge of approximately 65 cms; Figure 2). Operators will not know whether it is a dry, normal, or wet *year,* so they will not be able to adjust low-flow releases for year type. Instead, primary considerations for dry-season low-flow releases include:

1. Discharges < 30 cms pose challenges for transportation; 65 – 80 cms is considered optimal for transportation, but during portions of the dry season such a flow rate significantly exceeds the range of natural flows and will likely have negative impacts on ecological processes.
2. Natural flows rarely exceed 35 cms in April and May, and this period of low flows may be important for species' life histories. Management should strive to provide average daily flows during April and May that approach typical low-flow values, while maintaining adequate navigability (e.g., flows in excess of 30 cms should adequately support navigation).
3. The best way to preserve the natural intra- and inter-annual variability in dry season flows would be to adjust dam releases as some percentage of the inflows to the reservoir, e.g., to set dam releases at 100-125% of natural inflows.

Table 8. Dry season low-flow operational guidance:

1. Release flows of 30 cms or greater at all times.
2. Approach typical natural low-flow rates in April and May, adjusted to not hinder navigation (e.g., daily flows average approximately 30 cms in April and May).
1. Incorporate some degree of intra- and inter-annual variability by basing dam releases on inflow levels. For example, during the dry season, dam releases could be maintained within 100-125% of inflows.

Further research should investigate the ecological importance of low flows and whether the anticipated elevated low flows with hydropower operations will negatively affect ecosystem health. As discussed below, allowing dam releases to drop to natural dry-season flow levels will allow the reservoir to refill quicker and provide greater flexibility for releasing early wet-season high-flow pulses.

6.2.2. Early wet-season high-flow pulses

These pulses occur as short-duration peaks during the months of June, July and August. These pulses likely provide very important functions for various aquatic species and are the flow component that is most likely to be altered with dam operations, based on the simulated with-dam hydrology. At least one early wet-season pulse occurred in 25 out of 29 years of the hydrological record; 24 of these years had two or more pulses and in the years with a pulse the average number was 3. The simulated with-dam hydrology indicates that proposed dam operations will reduce or eliminate these pulses: in only 9 years out of 29 will there be any pulse and only five of these would have more than one pulse (Table 9).

Table 9. Early wet-season high flow pulses. 'Natural' refers to the number of events that actually occurred in the hydrological data; 'with-dam' refers to the number of events predicted to occur with status-quo dam operations; 'missing' is the difference between the previous two columns; 'recommended' refers to the # of events recommended (as per Table 4); 'deficit' is the difference between 'recommended' and 'with-dam' and represents the number of events that should be added through explicitly managed releases. Note that in this analysis, if an event did not occur in the natural hydrology then it is not counted toward the deficit. Thus, if the entry in "missing" is equal to zero, then "deficit" is also equal to zero (e.g, 1973). MAF = mean annual flow.

			Early wet season pulses (number of events)				
Year	**MAF (cms)**	**Year type**	**Natural**	**With-dam**	**"Missing"**	**Recom-mended**	**"Deficit"**
1973	83	dry	0	0	0	1	0
1974	110	normal	3	0	3	2	2
1975	161	normal	0	0	0	2	0
1976	99	normal	4	1	3	2	1
1977	117	normal	5	4	1	2	0
1978	130	normal	6	0	6	2	2
1979	223	wet	2	1	1	2	1
1980	175	normal	3	2	1	2	0
1981	138	normal	4	3	1	2	0
1982	179	wet	3	2	1	2	0
1983	126	normal	3	0	3	2	2
1984	130	normal	1	0	1	2	1
1985	79	dry	2	0	2	1	1
1986	170	normal	4	1	3	2	1
1987	124	normal	0	0	0	2	0
1988	156	normal	2	0	2	2	2
1989	121	normal	3	0	3	2	2
1990	160	normal	4	3	1	2	0
1991	121	normal	3	0	3	2	2
1992	101	normal	2	0	2	2	2
1993	190	wet	2	1	1	2	1
1994	111	normal	4	0	4	2	2
1995	191	wet	2	0	2	2	2
1996	138	normal	2	0	2	2	2
1997	129	normal	2	0	2	2	2
1998	194	wet	2	0	2	2	2
1999	180	wet	0	0	0	2	0
2000	79	dry	2	0	2	1	1
2001	56	dry	2	0	2	1	1

Reviewing the proposed with-dam hydrology, it appears that the reservoir refills with the first major high-flow event (a large high-flow pulse or a small flood) during the wet season. Based on the available record, the reservoir was etimated to refill in 28 out of 29 years. Once the reservoir has refilled, managed releases are predicted to be run-of-river during the rest of the wet season. The dam is projected to then release essentially constant flows during the dry season, until the reservoir again refills during the next wet season**.** In most years, 2-4 high-flow pulses are recommended to occur during this 'flat-line' period, including early and mid wet-season pulses. To examine the implications of managed high-flow pulse releases on reservoir refilling and operations, we simulated the effects of such releases using actual hydrology.

We developed a simple spreadsheet model that accounted for projected inflows to, and outflows from, the reservoir and kept track of the cumulative 'reservoir storage deficit' (based on inflow and projected outflow daily discharge data provided by Sinotech). The storage deficit increases (becomes more negative) during the dry season as projected outflows, holding steady near 65 cms, exceed inflow. At the end of the dry season, high-flow pulses generally begin to enter and refill the reservoir. When the reservoir storage deficit crosses "0" the reservoir has refilled and reservoir operations are projected to become run of the river (Figure 17).

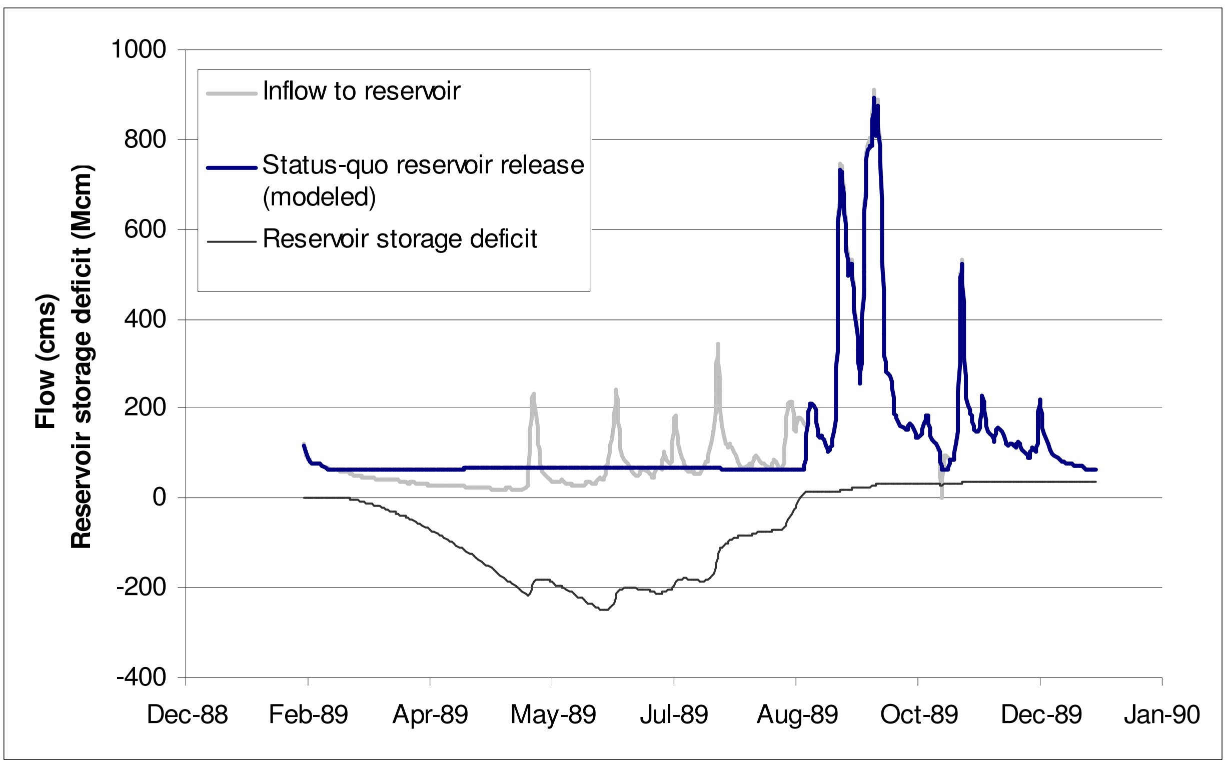

Figure 17. Projected reservoir inflows, outflows, and 'storage deficit' for 1989 hydrology and simulated dam operations; 1989 was a 'normal' year type in terms of annual discharge. This figure shows reservoir outflows based on status-quo with-dam hydrology (i.e., the outflow does not include any explicit managed releases for environmental flows).

Next, we examined the effect on reservoir refilling caused by releasing recommended early wet-season high-flow pulses, within the range of magnitude and duration described in Section 6.1. As an example, we simulated the release of two early wet-season high-flow pulses using 1978 hydrology, a 'normal' year type. As a simple rule, high-flow pulses were released only after a high-flow pulse entered the reservoir, and only the recommended two pulses were released, so that not all inflow pulses caused the release of a regulated high-flow pulse below the dam. With 1978 hydrology the reservoir is estimated to refill with status-quo reservoir operations by July 17; if the two recommended early-wet-season pulses had been released, the reservoir would have been filled on July 19 (Figure 18).

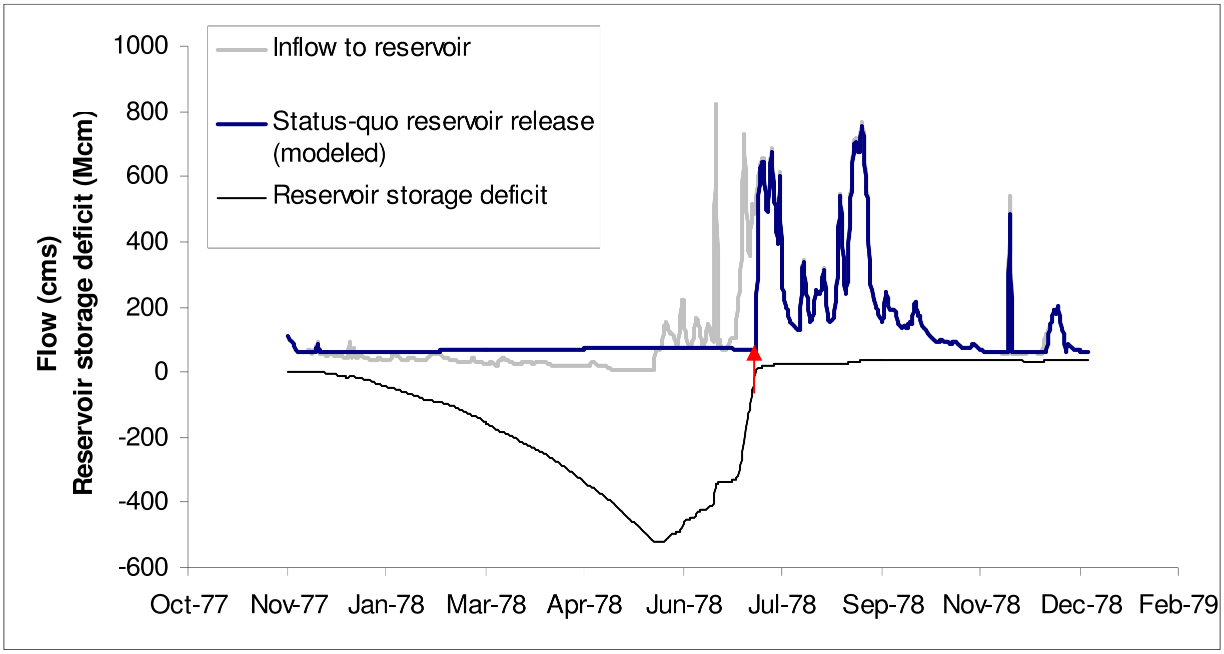

Figure 18a. Hydrology for 1978 (normal year) showing actual flows (inflow; light gray) and modeled with-dam operations (outflow; thick blue). The reservoir storage deficit begins at 0 with a full reservoir and declines during the dry season (thin black line). Run of river operations begin when the reservoir storage deficit returns to zero (full reservoir, indicated by red arrow).

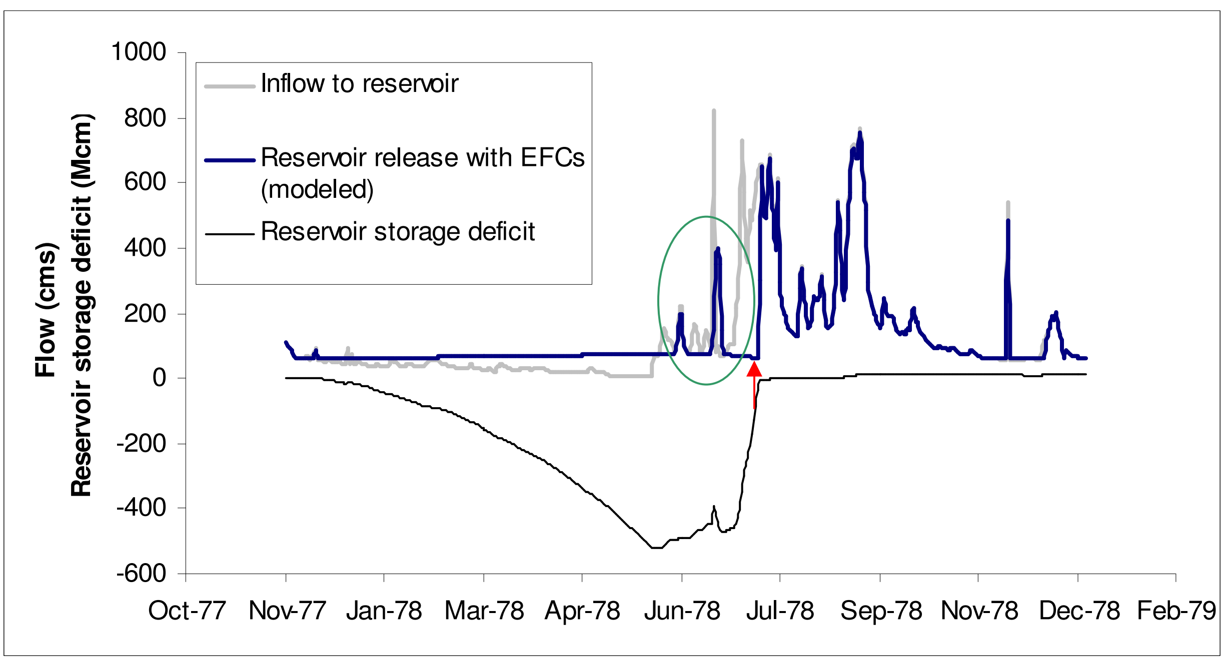

Figure 18b. Hydrology for 1978 with the addition of two early-wet-season high-flow (circled). Note that adding these pulses delays reservoir filling and the onset of 'run of river' operations by only 2 days (indicated by red arrow).

6.2.3 Mid-wet-season high-flow pulses

High-flow pulses naturally occurred during the middle of the wet season of every year, with an average of 4.5 events per year. Because in many years the reservoir is projected to fill early in the wet season, these EFCs are estimated to be less impacted by status-quo with-dam operations than the early-wet-season pulses (Table 10). With-dam operations are modeled to provide mid wet-season pulses in 27 out of 29 years, with an average of 3.2 events.

Table 10. Mid-wet-season high-flow pulses. 'Natural' refers to the number of events that actually occurred in the hydrological data; 'with-dam' refers to the number of events predicted to occur with proposed dam operations; 'missing' is the difference between the previous two columns; 'recommended' refers to the # of events recommended (e.g., at least 4 pulses regardless of year type as per Table 5); 'deficit' is the difference between 'recommended' and 'with-dam' and represents the number of events that should be added through managed releases. Note that in this analysis, if an event did not occur in the natural hydrology then it is not counted toward the deficit. In other words, if fewer events occurred naturally than were recommended, the 'deficit' is adjusted to reflect that (e.g., 1976, 1990, and 2001)

			Mid-wet-season flow pulses (number of events)				
Year	MAF (cms)	Year type	Natural	With-dam	"Missing"	Recom-mended	"Deficit"
1973	83	Dry	6	2	4	4	2
1974	110	normal	7	5	2	4	0
1975	161	normal	4	3	1	4	1
1976	99	normal	3	3	0	4	0
1977	117	normal	6	6	0	4	0
1978	130	normal	7	7	0	4	0
1979	223	Wet	5	5	0	4	0
1980	175	normal	7	7	0	4	0
1981	138	normal	4	4	0	4	0
1982	179	Wet	5	5	0	4	0
1983	126	normal	6	6	0	4	0
1984	130	normal	5	3	2	4	1
1985	79	Dry	5	1	4	4	3
1986	170	normal	4	4	0	4	0
1987	124	normal	4	3	1	4	1
1988	156	normal	4	2	2	4	2
1989	121	normal	4	2	2	4	2
1990	160	normal	3	3	0	4	0
1991	121	normal	3	0	3	4	3
1992	101	normal	3	2	1	4	1
1993	190	wet	5	5	0	4	0
1994	111	normal	4	3	1	4	1
1995	191	wet	3	2	1	4	1
1996	138	normal	3	2	1	4	1
1997	129	normal	3	2	1	4	1
1998	194	wet	4	1	3	4	3
1999	180	wet	5	3	2	4	1
2000	79	dry	8	3	5	4	1
2001	56	dry	2	0	2	4	2

We used the same simulation approach described above to test the implications on reservoir management of releasing mid-wet-season high-flow pulses. We simulated adding both early-wet-season and mid-wet-season pulses to two of the three driest years on record, to examine the implications for reservoir management in some of the most extreme years. With 1985 hydrology, reservoir filling is delayed by 8 days (from 10/27 with status-quo reservoir operations to 11/4 with the release of the pulses; Figure 19) and with 2000 hydrology, filling is delayed by 14 days (from 9/17 to 10/1; Figure 20).

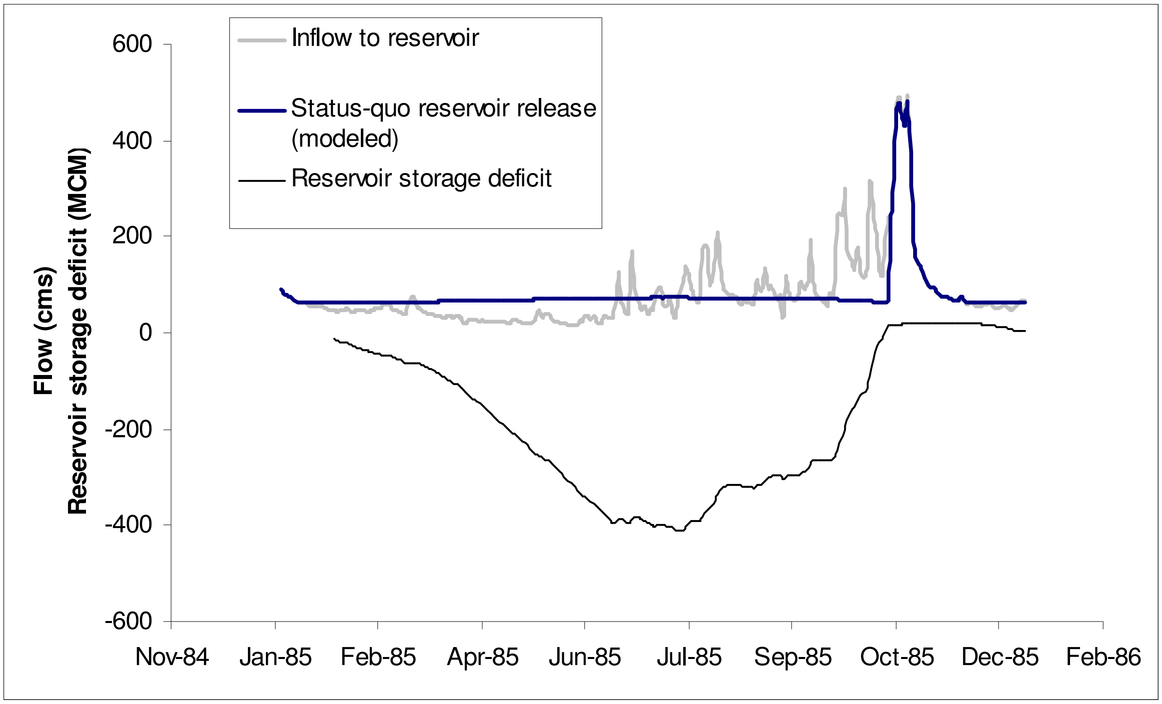

Figure 19a. Hydrology for 1985 (dry year) showing actual flows (or inflow to reservoir; light gray), modeled flow with dam operation (outflow; thick blue), and reservoir storage deficit (thin black line).

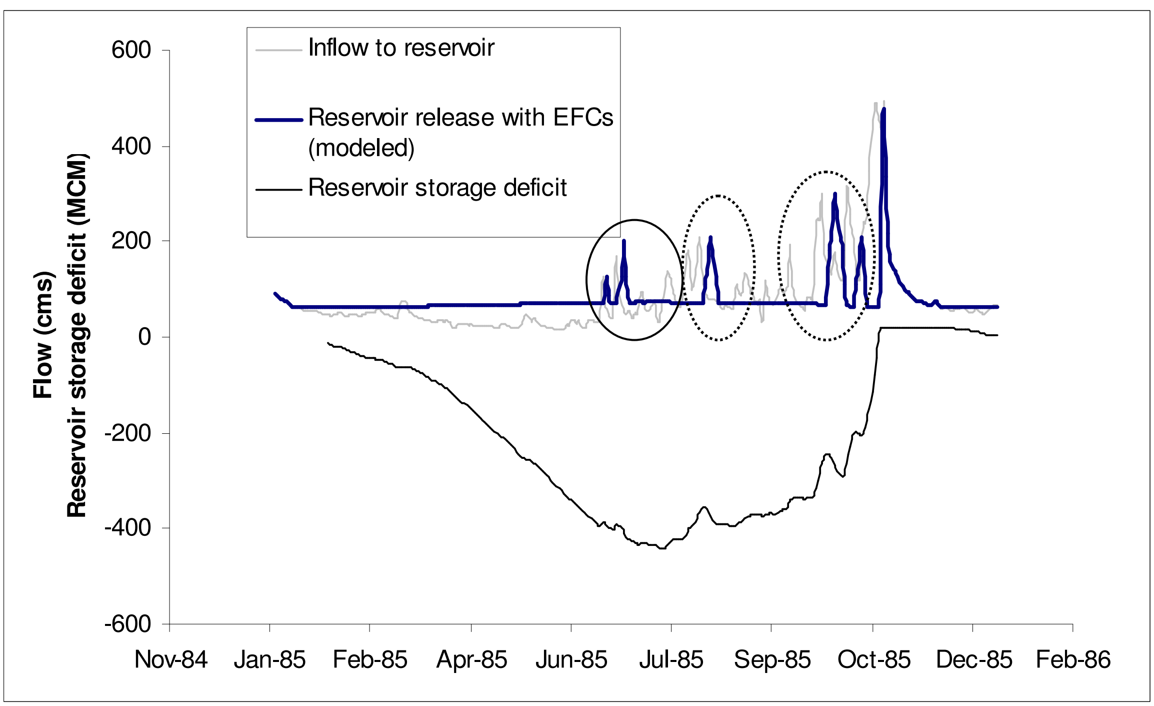

Figure 19b. Hydrology for 1985, but adding two early-wet-season high-flow pulses (within solid circle) and three mid-wet-season high flow pulses (within dashed circles). Note that adding these pulses delays reservoir filling and the onset of 'run of river' operations by only 8 days.

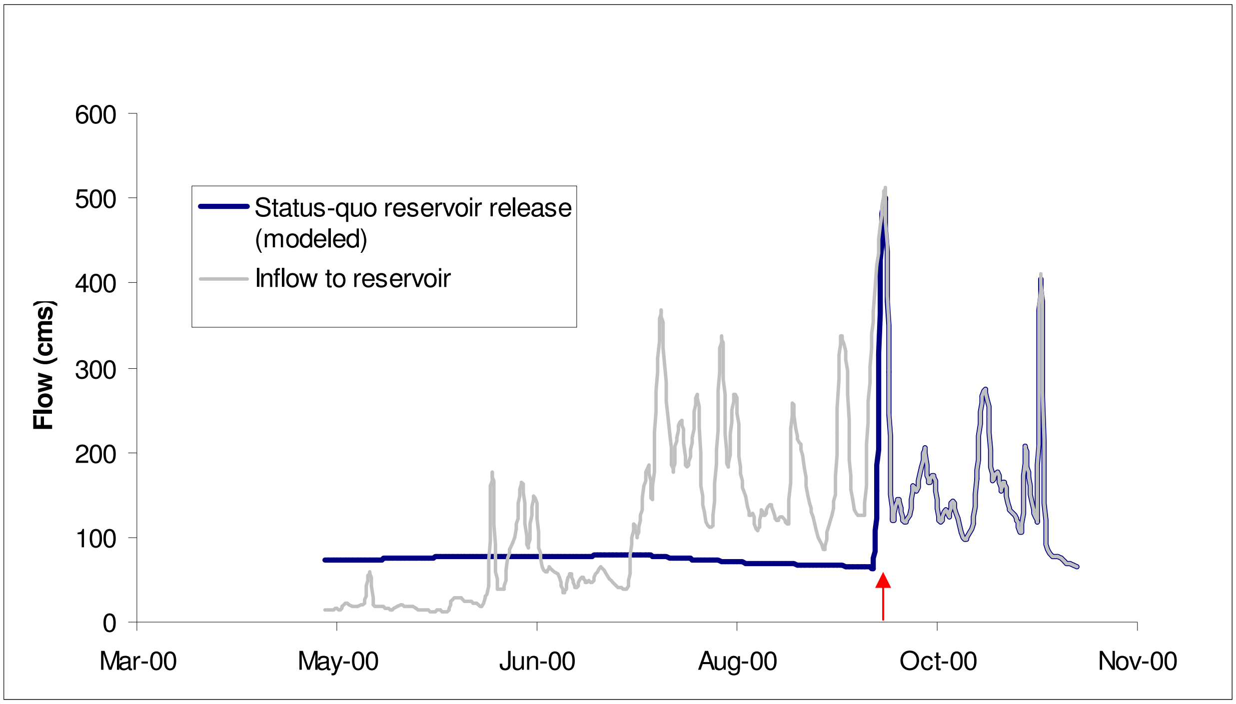

Figure 20a Hydrology for 2000 (dry year) showing actual flows (inflow; light gray) and modeled with-dam operations (outflow; thick blue).

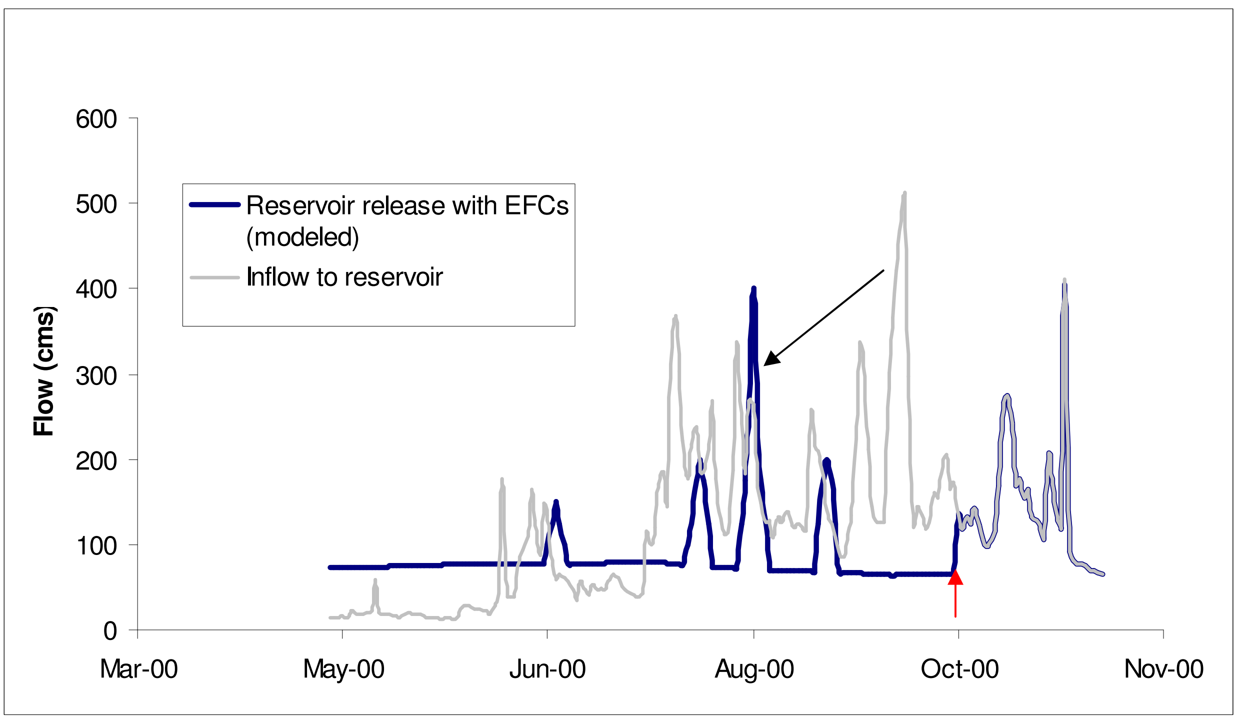

Figure 20b. Hydrology for 2000 with the addition of two early-wet-season high-flow pulses and two mid-wet-season high flow pulses. Note that adding these pulses delays reservoir filling and the onset of 'run of river' operations by 2 weeks (indicated by red arrows) and 'trades' a naturally occurring pulse that occurs in September for a managed release high-flow pulse in

(Figure 20b caption continued): August; in the status-quo scenario this naturally occurring September pulse is released because the reservoir is full, in the scenario that adds managed pulses, this natural pulse is captured by the reservoir and fills it, compensating for earlier managed releases. The black arrow originates with the September pulse that would have been released under status-quo reservoir operations and points to the managed August release.

If dry-season low-flow releases were decreased from projected status-quo operations such that they approached typical (historical) low-flow values, then the reservoir would tend to refill faster. For example Figure 21 shows 1985 hydrology with decreased dry-season flow releases. With this scenario, the release of four high-flow pulses reduces the time to filling by only two days rather than the eight days indicated in Figure 6.

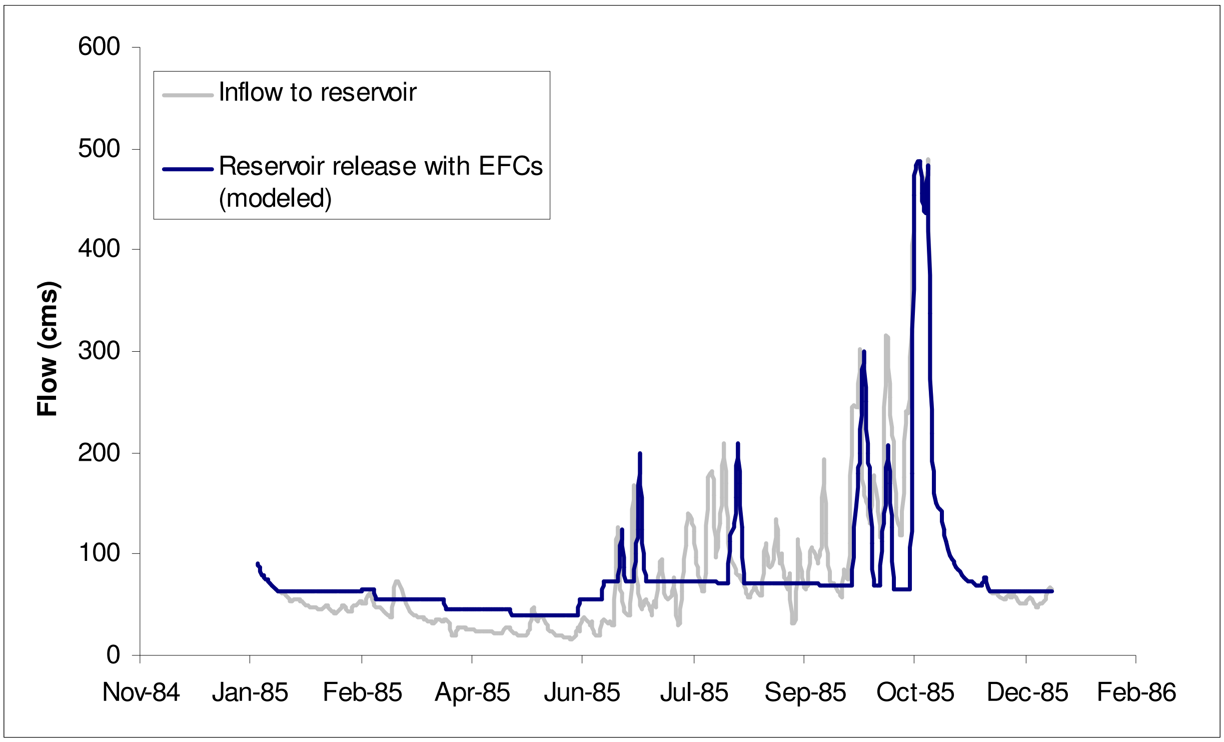

Figure 21. Hydrology for 1985 (a dry year) adding early and mid wet-season high-flow pulses and decreasing dry-season reservoir releases (relative to projected status quo operations) toward typical (historic) values.

In 2001—by far the driest year in the record and the only year in which the reservoir would not have refilled—the release of recommended pulses during the early and mid wet-season pulses (releasing flows only after a natural pulse event had occurred) would have affected reservoir operations for approximately one month. With projected status quo operations and 2001 hydrology the reservoir releases would have passed below the threshold for generation, and essentially became run of the river *with low flows*, on February 4, 2002. If managed pulses had been released in 2001, this condition would have been reached on January 5, 2002. With projected status-quo operations the reservoir would have refilled again and become run of river in August 29, 2002 in both scenarios (Figure 22). In any given year, managers will not know the river is experiencing an extreme drought until the high flows of October fail to arrive. By that date, the managers may have released some high-flow pulses based on the EFC recommendations and this operation guidance. In the extreme drought modeled here, following this operational guidance would affect hydropower operations by one month.

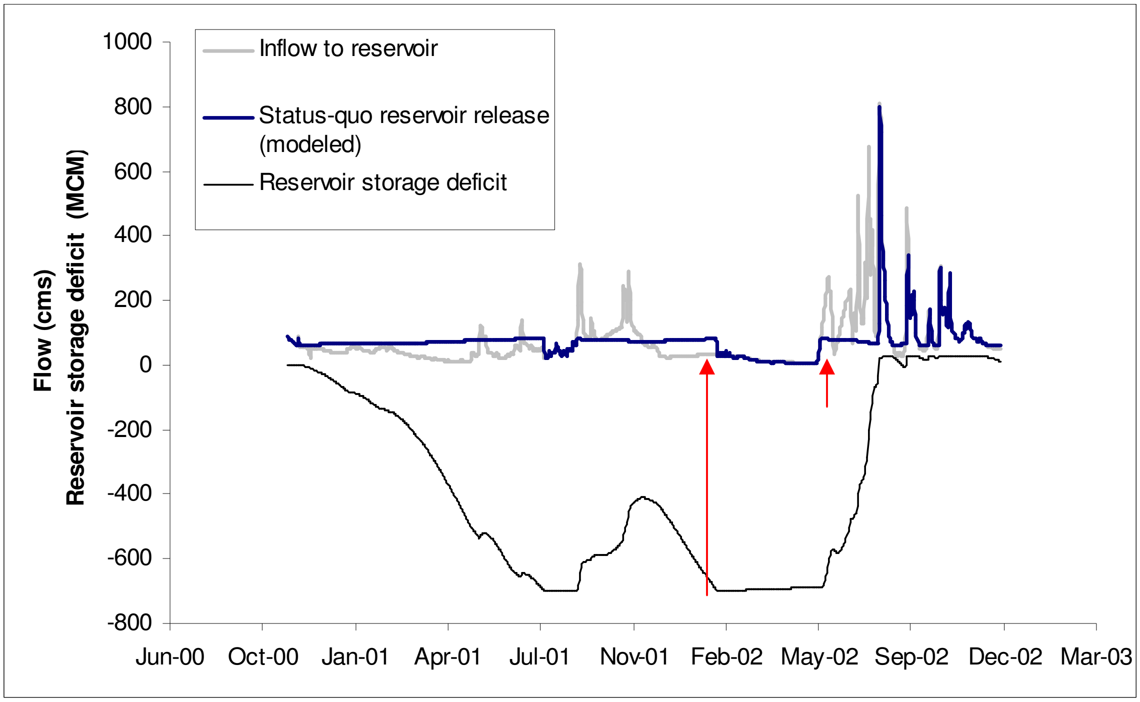

Figure 22a. Hydrology for the driest year on record, 2001, the only year with hydrology such that the reservoir would not have filled. The reservoir would have filled in August of the following year.

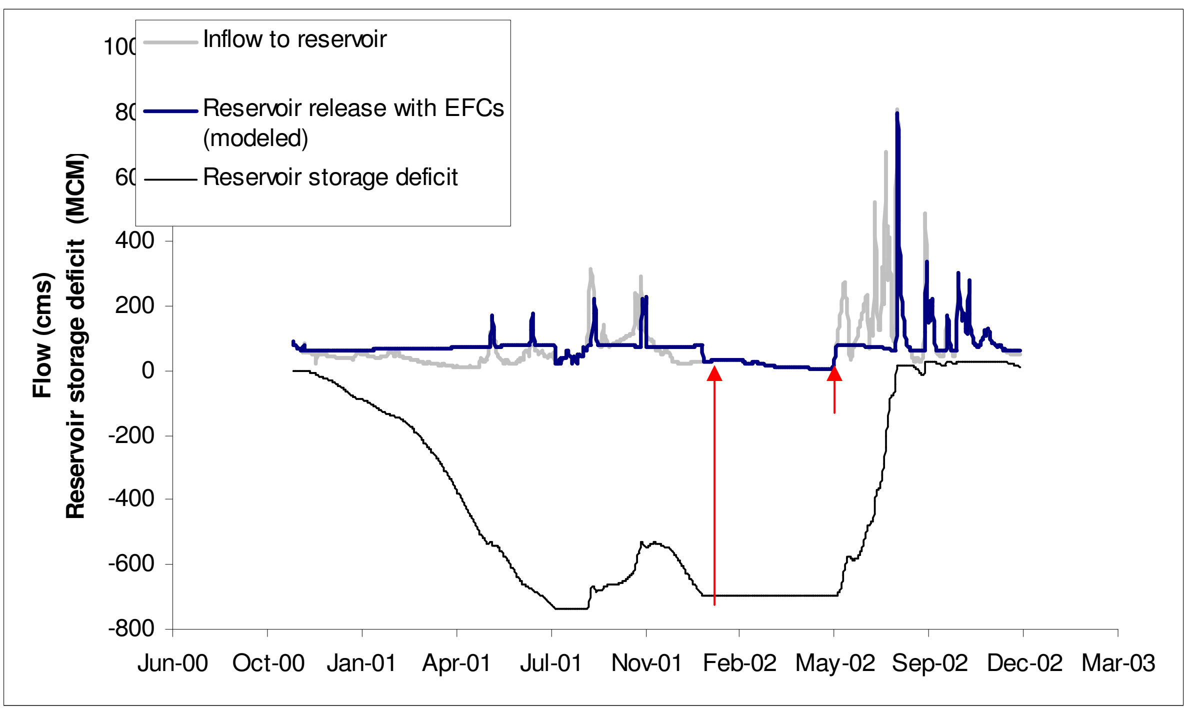

Figure 22b. Same hydrology as above but with the addition of four high-flow pulses during 2001. Because of these pulses the reservoir would have dropped below the threshold for generation approximately one month earlier than in the figure above (noted by long red arrows). In this scenario the reservoir would have filled again on the same day (short red arrows).

Table 11. Early- and mid-wet-season high-flow pulse guidance:

1. In nearly all years, early and mid wet-season high-flow pulses can be released without appreciably affecting reservoir refilling or operations
2. Reservoir managers can release the recommended number of high-flow pulses in response to inflow events. The magnitude of the pulse can be scaled to the inflow and the reservoir level. This will lead to the release of fewer and smaller pulses in very dry years, larger and more frequent pulses in wet years. If no high-flow pulses enter the reservoir during the early wet season, then managers will not need to release downstream pulses for that time period.

6.2.4 Floods and late wet-season high-flow pulses

The reservoir has relatively little storage capacity and is not designed to provide flood control. Therefore, floods are expected to pass through the reservoir unaffected (inflow = outflow) and, with anticipated dam management, operators will not need to managed or "provide" flood flows.

Because the reservoir is estimated to fill nearly every year, the simulated with-dam operations indicate that late wet-season pulses will not be affected by the dam, as they pass through a full reservoir. With anticipated dam management, operators will not need to "provide" late-wet-season pulses.

Table 12. Flood and late-wet-season high-flow pulse guidance:

2. Floods and late-wet-season high-flow pulses are not predicted to be affected by dam operations.
3. Therefore, reservoir operators will not need to 'manage' for these flow events.

6.2.5 Summary of Operational Guidance

1. *Dry season low flows.* Proposed, status-quo dam-released daily average low flows are anticipated to be considerably elevated above natural low flows, particularly in April and May (Figure 2). Dry-season dam operations should be modified to allow dam-released low flows to approach natural low values, with consideration given to transportation needs (> 30 cms). Low flow operations should also strive to incorporate some intra- and inter-annual variability by setting dam releases at a percentage of natural inflows. Further research should elucidate the ecological importance of low flows and whether the anticipated elevated low flows with hydropower operations will negatively affect ecosystem health and local people.

2. *Early-wet-season and mid-wet-season high-flow pulses*. Simple modeling indicates that the recommended number of pulses can be released in nearly every year without appreciably affecting dam operations. Therefore, managers can release high-flow pulses as the reservoir is refilling as a function of inflows. Early in the season, and based on reservoir level, managers could release smaller pulses (i.e., smaller than the inflow pulse); with greater confidence in refilling managers can release larger pulses. There appears to be very low risk in releasing early and mid wet-season pulses (in terms of reservoir refilling) and the hydrographs with managed releases look fundamentally improved compared to status-quo hydrographs from the standpoint of mimicking the natural historical variability (e.g., compare 'a' and 'b' scenarios in Figures 19 and 20). ***Therefore, releasing such pulses as a function of inflow is a relatively low-risk method for maintaining a more natural hydrograph***. More sophisticated and appropriate rules and guidance can be developed to inform these management decisions and TNC welcomes the opportunity to contribute to the development of such guidance.

3. *Floods and late-wet-season high-flow pulses*. These flows are not anticipated to be affected by dam operations so managers will not have to provide for them.

6.3 The effects of hydropower peaking on downstream rivers

Peaking operations represent one of the most serious environmental impacts of many hydropower projects. Peaking flows occur when a reservoir is operated to provide power only during portions of a day or week (typically with rapid rates of change in flow). During the periods between power generation, flows are typically curtailed or very low, and may result in impacts such as drying of the river bed and stranding of aquatic biota. During generation, flows are greatly increased. This results in a rapid rise and fall of river flow and stage between the periods of generation and non-generation. Viewing river flows on a daily average basis can be quite misleading; dramatic changes in discharge within a day can be masked when calculating flows as daily averages, as illustrated in Figure 23, which shows rapid fluctuations each day between the non-generation period (25 cms) and the generation period (135 cms), producing a steady daily average of 62 cms.

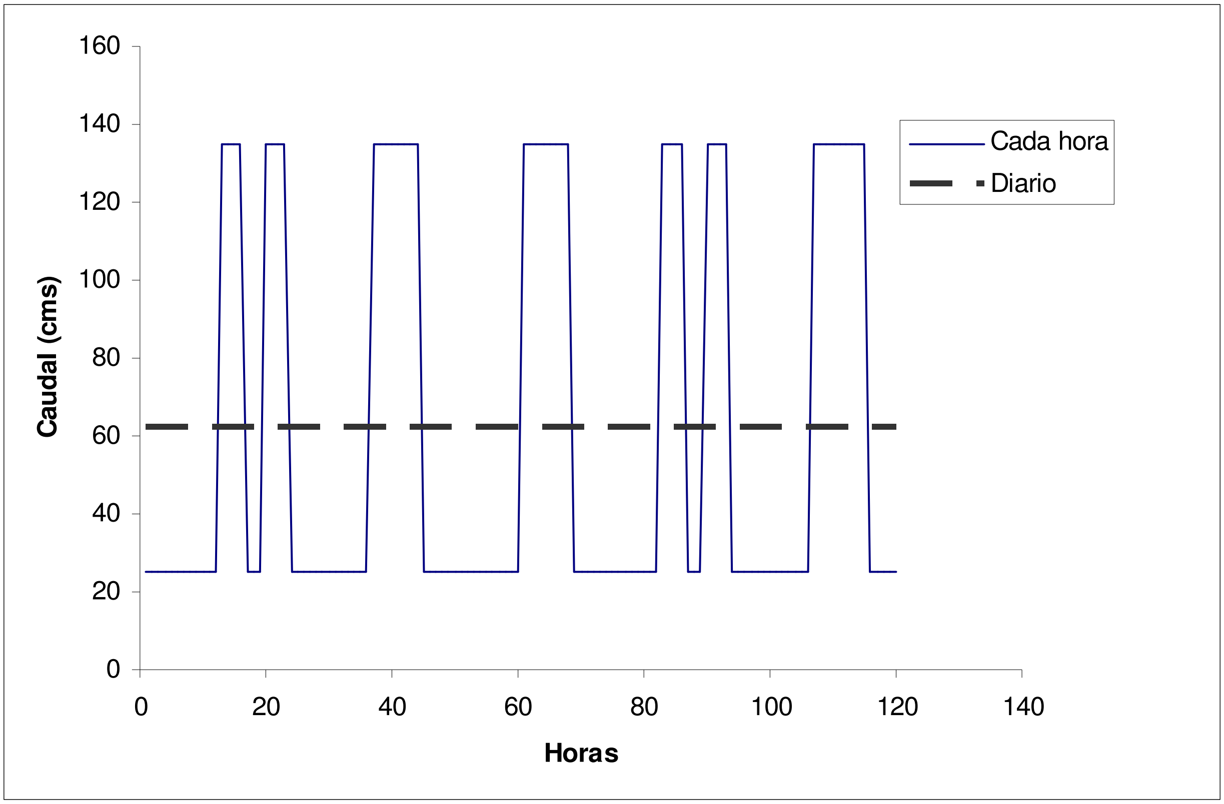

Figure 23. Daily peaking operations (blue line) that fluctuate between 25 and 135 cms and produce a steady daily average of 62 cms.

Peaking flow operations have no natural analog in a free-flowing river, and thus represent a novel condition to which aquatic species are not adapted. For this reason, peaking operations stress aquatic ecosystems highly and can have marked effects on river structure and on the biotic communities in the downstream reaches affected by the strong daily changes in discharge and river stage.

Below we provide general information about the effects of peaking operations on river ecosystems, organized by the specific characteristics of the peaking flow hydrograph known to influence biotic communities and navigation (Figure 24). The particular components of the peaking hydrograph that are associated with ecological impact are as follows:

- *Up-ramping rate* – the rate at which discharge or water levels increase as a function of time as flow levels are increased for generation (measured as the change in discharge/hour or change in stage/hour).

- *Peak discharge magnitude* – The maximum discharge or water level reached in a given peaking event (measured in terms of discharge (cms) or stage).

- *Down-ramping rate* – the rate at which discharge or water levels return to minimum flow after the peaking event (measured as the change in discharge/hour or change in stage/hour).

- *Minimum flow* – The flow released between periods of generation (in terms of discharge or stage).

Below, the ecological consequences for each of the four peaking flow components are discussed.

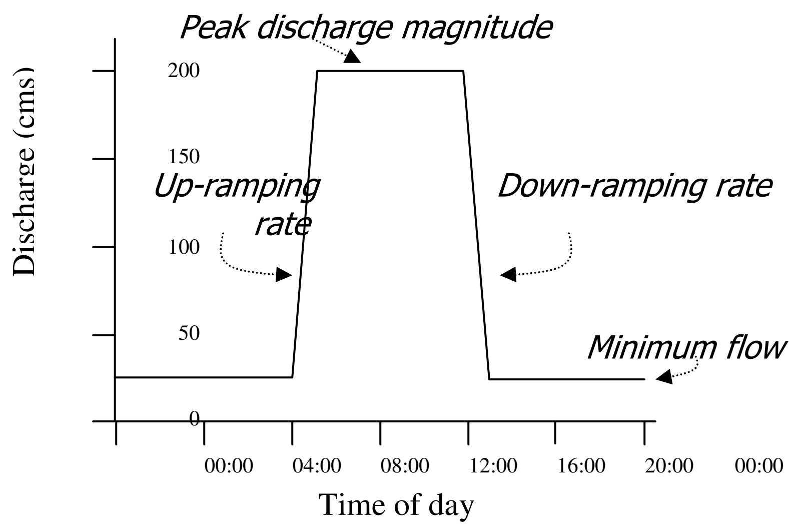

Figure 24. A hypothetical hydrograph for the river just below a dam being managed with daily peaking operation. In the night and early morning, discharge from the dam is at its minimum (25 cms) until peak electricity demand begins (06:00), when discharge rises sharply to about 200 cms for 8 hours and then returns to minimum flow. The different parts of the hydrograph that can be managed to reduce ecological disruption include the up-ramping rate, the peak discharge, the down-ramping rate, and minimum flow.

Up-ramping rate

Up-ramping refers to the change of river discharge or river stage per unit time as river flow is increased from its daily minimum to its peak discharge magnitude. As a river is up-ramped, the organisms living in the river experience a rapid change in flow conditions. This rapid increase in flow can have the following consequences for downstream ecosystems:

- *"Catastrophic drift" and biotic impoverishment*. Intense daily flow peaks can physically flush aquatic invertebrates and fishes from reaches affected by peaking because of the increased shear stress caused by rising water velocities. This causes invertebrates to enter the water column and float downstream to more suitable habitats in a process called "catastrophic drift". The end results of this are an impoverished biotic community (lower overall diversity, abundances and biomass of invertebrates and fishes) (Cushman 1985, Moog 1993, Lagarrigue et al. 2002). This biotic impoverishment can be exacerbated by the presence of an upstream reservoir through which many invertebrates cannot pass, thereby eliminating the possibility of upstream replenishment (Moog, 1993; Lauters et al., 1996). The removal of shrimps and insects—important links in riverine food webs—through catastrophic drift can reduce the availability of food items for fishes (Moog 1993). Fishes can also be flushed downstream with larval and juvenile stages being particularly vulnerable. This flushing can result in less diverse fish assemblages that have lower recruitment of young fishes to adult life stages, and lower overall abundances compared to natural conditions (Troelstrup and Hergenrader 1990).

Peak discharge magnitude

The physical power of water flow in a river channel is responsible for the shape, size, and sediment composition of a river channel, its banks and floodplain, and the distribution of habitats within the channel where organisms can live and reproduce (Leopold et al. 1992).

- *Reduced river and floodplain habitat diversity*. Water released from a dam is relatively free of sediments and consequently has a high erosive capacity. Frequent high flows due to peaking can scour the river channel and carry away small sediments leading to an “armored” channel that is lined with larger cobbles, boulders, and bedrock (Kondolf 1997). The removal of smaller diameter sediments leads to a reduction in the diversity of habitat types available to aquatic life (Kondolf and Wolman 1993), which can lead to a less diverse biotic community (Gumiero and Salmoiraghi 1994). The erosive capacity of peaking flows can also cause “downcutting” of the channel base, leading to an unnaturally deep channel with high banks. A channel affected by downcutting will interact with its floodplain less frequently, which can adversely affect the diversity of floodplain features and floodplain life (Graf 2005).

- *Reduced biotic diversity*. As mentioned above, high peak discharges affect the diversity of physical habitats available in the river, banks, and floodplain. Reduced habitat diversity has been clearly correlated with reduced species diversity within biotic communities (Moog 1993), and potentially also with altered ecosystem function (e.g., the cycling of nutrients). This reduction of species diversity affects not only river ecosystems, but can also impact wildlife that utilize floodplain and riparian habitats (Graf 2005).

- *Direct effects on biota*. Much as the up-ramping rate can flush and physically remove organisms from an affected river reach, the strength of this change depends in part on the peak discharge magnitude, and also on the duration of peak discharge. See *“Catastrophic drift” and biotic impoverishment* in the previous section for details.

Down-ramping rate

The flow change associated with the transition from peak generating flow to minimum flow levels is called down-ramping. Many scientific studies on down-ramping have documented the impacts of this river management activity on organisms in rivers, and fairly specific numeric guidelines exist for minimizing impacts on aquatic life. Impacts associated with down-ramping include:

- *Fish and aquatic invertebrate mortality associated with drying* – Fishes experience increased mortality when rapid lowering of water occurs, because animals become stranded in side channels, back pools, and in substrates subject to drying. Stranded fishes are prone to asphyxiation, unsuitable water quality, or predation from birds. Young-of-the-year, juvenile fishes, and other fishes associated with back pools prone to isolation are most affected (Hvidsten 1985, Bradford et al. 1995, Scruton et al. 2003, Berland et al. 2004). Flow fluctuations and dewatering can result in the washout, stranding and/or concentration of macroinvertebrates in shallow areas, particularly along river margins (Petts 1984; Cushman 1985).
- *Navigational disruption.* Boat navigation would clearly be affected if flow fluctuated on a daily basis from the level of a wet season flood pulse to normal dry season base flow levels to in the course of an hour. Pipanteros will have to adapt to the changing navigational conditions, but they may benefit from a regular schedule for up and down ramping to occur.

Minimum flows
Hydroelectric dams engaged in peaking often release a minimum flow between periods of power generation. If this flow is too low, river channels can become dewatered and longitudinally discontinuous (i.e., pools separated by dry riffles). Extreme low flows can impact aquatic species through poor water quality (e.g., water temperature, dissolved oxygen) and vulnerability to predation, due to shallow and/or disconnected habitat units.

7.0 Research and monitoring questions

The linkages between the EFCs and river processes contained in this report largely represent hypotheses that should be tested and refined through targeted monitoring and research. Very few scientific studies or data sets exist from the Patuca River and so there remains a great need to better understand the river's basic physical and ecological processes and how these processes provide the desired benefits for the communities. Below is a set of issues that were identified as uncertainties or research priorities during the workshops and which should be addressed through future targeted monitoring and research studies. Not all of these issues are directly related to the environmental flow assessment, but were identified by workshop participants as key issues.

Fish and other aquatic organisms

- The extent to which migratory fish and shrimp species utilize habitats above the dam site, and the effect that a barrier to migration would have on migratory populations, including fisheries used by human communities, both above and below the proposed dam site. In addition to research on the direct effects of a migration barrier on migratory populations, research should also examine the effects on ecosystem processes from changes to these populations (e.g., changes to food webs, trophic cascades, etc.).
- Basic life history information on many of the fish species, including fidelity to natal rivers and relationships between flow events and life history events and behavior.
- Potential refugia for migratory species should the habitats above the dam site (1/3 of the watershed area) get cut off to up-migrating fishes and shrimps.

Geology and sediment

- Rates of sedimentation in the reservoir.

- Basic sediment budget for the basin; how much sediment will be supplied by tributaries downstream of the dam site? How will the dam, and the trapping of sediment, affect sediment dynamics downstream of the dam, including channel morphology and floodplain development?
- Assess the seismic risk of the proposed dam site.

Discharge, stage, and cross sections
- River stage and discharge measurements at various locations, to better understand which channel and floodplain surfaces would be inundated at various flows.
- Cross-sectional surveys of the channel to better understand relationships between flow, wetted channel, and channel hydraulics.

Hydropower peaking
- It is anticipated that Patuca III will only rarely be operated for hydropower peaking. However, even relatively short periods of peaking may impact river geomorphology, aquatic biota, and transport. Therefore, analyses should be conducted to estimate the fluctuations in discharge, stage, and velocity that would accompany hydropower peaking operations. Further, research studies should investigate the implications for such fluctuations on channel morphology, aquatic biota, and transport and should also determine the distance downstream within which these fluctuations and associated impacts will be significant.

Dam operations and Environmental Flow Components (EFCs)
- This report provides a basic analysis of dam operations and how releases from the dam could provide for most or all of the recommended EFCs. However, this analysis could be made more rigorous to confirm these results and to produce operating guidance that is as relevant and useful as possible to future dam operators.

Human communities
- What discharge corresponds to a flood that is considered destructive by human communities?

Monitoring and adaptive management
- **An effective plan should be developed for monitoring of resources and adaptive management of the river. This monitoring plan should:**
    - **test and refine the hypotheses about the relationships between EFCs and important river processes and conditions**
    - **investigate the questions and uncertainties described above**
    - **focus on the most important human and natural resources to monitor their status prior to, during, and after dam construction and operation. These include populations of species that are particularly important for river food webs and human communities, including invertebrates, fish, and reptiles. Both migratory and resident species should be monitored. Monitoring should also focus on channel morphology at various distances below the dam.**

- **include a feedback system for receiving information from affected communities, should managed discharges prove detrimental to critical aspects of livelihood**
- Improved climatological monitoring.

8.0 Conclusions

The environmental flow assessment described in this report drew on a variety of sources, including local community knowledge, scientific studies from similar tropical rivers, hydrological analyses, and the perspectives of a wide range of interdisciplinary scientists and stakeholders who participated in the workshop. The Environmental Flow Components (EFCs) described in this report are a preliminary assessment of the flow conditions that will minimize the negative consequences of the proposed hydroelectric project with regard to altered flow regime. In part because of the lack of scientific studies or data for the Patuca, these EFCs, and their linkages with riverine conditions and processes, should be viewed as hypotheses that should be tested and refined through targeted monitoring and research. Further, there are a number of unknowns and uncertainties that should also be investigated (described in Section 7.0). Therefore, a rigorous and science-based plan for monitoring and adaptive management should be developed and implemented prior to dam construction.

Because it is anticipated that Patuca III will only rarely be operated for hydropower peaking (i.e., large daily fluctuations in flow release levels), this report provides only general guidance and information about hydropower peaking. Because even relatively infrequent peaking operations may have significant effects on channel morphology, aquatic biota and transport, the details of possible peaking operations should be carefully examined along with the potential associated impacts.

The field trips, workshop, and other investigations revealed that the Patuca River is an extremely important ecosystem for both human communities and for fish, wildlife and biodiversity. This report describes the flow conditions, in terms of EFCs, that are hypothesized to be capable of maintaining these values. Initial analyses described in this report suggest that the proposed operations of Patuca III will provide a number of these recommended EFCs because they tend to occur when the dam is projected to be operating as 'run-of-river.' Conversely, early and mid wet-season high-flow pulses may not occur with projected dam operations because these EFCs tend to occur while the reservoir is still refilling. These EFCs may be extremely important for fish migrations and reproduction. A simple analysis suggests that by minimally modifying the dam operation plan, the dam could provide these EFCs in nearly every year with relatively small effects on hydropower operations and reservoir refilling. This analysis provides reason for optimism that operations of Patuca III can be adjusted to provide downstream flows that approximate historical conditions to which ecosystems and human communities are adapted. Future research—on both dam operations and on river processes—can provide further insights on how to improve the compatibility between dam operations, the river ecosystem, and human communities affected by the Patuca 3 project.

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Patuca River Environmental Flow Assessment

Appendices

Appendix 1: Memorandum of Understanding between the Empresa Nacional de Energía Eléctrica (ENEE) and The Nature Conservancy (TNC)

Appendix 2: Preliminary Indicators of Hydrologic Alteration Analysis for the Patuca River (by Jeff Opperman)

Appendix 3: Ecological and Social Impressions of the Middle Patuca River and Potential Consequences of the Patuca 3 Hydropower Project (by Peter Esselman)

Appendix 4: Summary report of the Patuca River Environmental Flows Workshop (November, 2006).