ECOLOGICAL AND SOCIAL IMPLICATIONS OF HYDROPOWER DEVELOPMENT ON A NEOTROPICAL RIVER SYSTEM, COSTA RICA

by

ELIZABETH ANDERSON OLIVAS

(Under the Direction of Catherine M. Pringle)

ABSTRACT

The Sarapiquí River system is one of several watersheds in Costa Rica currently undergoing rapid hydropower development. As of 2004, eight hydropower plants are in operation, one project is under construction, and additional hydropower developments are being planned for the Sarapiquí. This dissertation examined hydropower development in Sarapiquí at national, watershed, and local scales. At a national / regional scale, this study showed that partial privatization of electricity generation during the past two decades has driven hydropower development in Sarapiquí and on other Central American river systems. In Costa Rica, ~28 private hydropower plants have been constructed since 1990; six of these are located in the Sarapiquí watershed. At a watershed scale, I examined the cumulative effects of hydropower development on the hydrologic connectivity of the Sarapiquí River system. Hydropower plants have dewatered 30.9 river kilometers in Sarapiquí and roughly 10% of stream length in the watershed is now located upstream from dams. The cumulative effects of hydropower development on the ecological integrity of the watershed may interact with the effects of other human disturbances in the watershed, such as deforestation and increasing fishing pressures. On a local scale, I examined the effects of the Doña Julia Hydroelectric Center on stream fish assemblages of the upper Puerto Viejo River. The presence of a diversion dam influenced fish assemblage composition near the dam and along a dewatered reach of stream. This dissertation also examined socio-environmental conflicts associated with hydropower development in Sarapiquí. Here, I document the multiple uses of the Sarapiquí River and examine the role of hydropower as a catalyst for river conservation activities in the watershed. The case study presented in this dissertation may be applicable to other tropical watersheds currently undergoing hydropower development.

INDEX WORDS: hydropower, dams, Costa Rica, tropical, fish, stream ecology, cumulative effects assessment, conservation

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DEDICATION

Para la gente de Sarapiquí. Mil gracias por su apoyo y espero que sigan luchando para conservar la belleza natural del Río Sarapiquí.

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CHAPTER 1:

GENERAL INTRODUCTION

This dissertation examines some of the ecological and social consequences of hydropower development in the Sarapiquí River watershed, Costa Rica. Like many other river systems in Costa Rica, the Sarapiquí has experienced a recent proliferation of dams for hydropower. Since 1990, eight hydropower dam projects have been built in Sarapiquí and several additional projects are in planning or construction stages. Dam construction in Sarapiquí and other parts of Costa Rica is motivated by the country's expanding human population (presently at 4 million) and increasing demand for electricity, estimated at 6% annually. Unlike most developing countries, the vast majority of Costa Ricans (97%) have electricity in their homes. Hydropower is the primary source of this electricity, accounting for roughly 85% of electricity produced domestically.

Worldwide, hydropower dams provide approximately one-fifth of electricity. However, in many tropical developing countries, such as Costa Rica, hydropower satisfies nearly 100% of electricity needs, and is perceived as an important link to national development (WCD 2000). While the rate of dam building peaked in the U.S. during the middle of the last century, the number of dams built per year is on the rise in many tropical, developing countries. In Costa Rica, more than 30 dams were constructed during the 1990s. The majority of these dams are small (<15 m high) and privately operated.

Hydropower dams have often been the subject of controversy due to their complex environmental, social, political, and economic impacts. A substantial amount of information exists on the effects of large dams on temperate rivers (Ward and Stanford 1979; Goldsmith and Hildyard 1984; Dynesius and Nilsson 1994; Rosenberg et al. 1997; Pringle et al. 2000). Although small dams are a more pervasive feature in the landscape, their effects have not been as well studied (Gleick 1992; Graf 1999). Moreover, studies of basic stream ecology and the effects of dams are generally lacking for many tropical regions (Pringle et al. 2000). This dissertation addresses these two gaps in the scientific literature and provides answers to questions related to the effects of small dams on a tropical river system.

Project history and study scope

The research presented here actually began in 1998, when conservationists and community leaders from Sarapiquí County, Costa Rica approached Dr. Catherine Pringle to express their concerns about the impacts of rapid hydropower development on rivers in the region. At that time, Dr. Pringle had been working on streams in Sarapiquí for about 15 years (see www.arches.uga.edu/~cpringle; STREAMS project link) and was locally known for her efforts to develop river conservation activities in the region (Laidlaw 1996; Vargas 1995; Pohlman 1998; Pringle 1999). In the fall of 1998, while working with Dr. Pringle, I started communicating with Orlando Vargas, an employee of La Selva Biological Station, which is operated by the Organization for Tropical Studies (OTS) in Sarapiquí, Costa Rica. With the help of Orlando and Rosa Sandoval, also an OTS employee at the time, I began collecting information about hydropower development in the Sarapiquí watershed. In January 1999, I made my first visit to Costa Rica to meet with OTS and other conservationists in Sarapiquí. In three days, I visited many rivers in the watershed and interacted with community groups concerned about further dam construction. I left Costa Rica with plans to return and investigate the ecological and social impacts of hydropower development in Sarapiquí.

In June and July of 1999, I spent roughly six weeks in Costa Rica meeting with stakeholders involved with hydropower development in Sarapiquí. Among the stakeholders were the Costa Rican Institute of Electricity (ICE), the Minister of Environment and Energy (MINAE), the Public Services Company of Heredia (ESPH), the Municipality of Sarapiquí, the Association for the Environmental Well-Being of Sarapiquí (ABAS), the Sarapiquí Bureau of Tourism (CATUSA), and many residents of Sarapiqui County. I also visited the Doña Julia hydropower project, then under construction on the Puerto Viejo River, as well as the town of La Virgen, where a hydropower project was being proposed by the ESPH. Based on these initial informal interviews with stakeholders during my two visits to Costa Rica, I identified four major questions that needed to be answered regarding hydropower development in the Sarapiquí watershed. I spent the next four years (2000-2003) of my graduate career addressing these four questions as reflected by the subsequent chapters of this dissertation.

Question 1: ***Why is the Sarapiquí watershed a target for rapid hydropower development?*** In Chapter 2, I consider the importance of hydropower in Costa Rica and other Central American countries. I also discuss private companies' participation in electricity generation in Central America and outline the ecological consequences of recent electricity reforms. I then examine the relationship between partial privatization of electricity generation in Costa Rica and rapid hydropower development in the Sarapiquí and other watersheds.

Question 2: ***What are the cumulative effects of multiple dams on the ecological integrity of the Sarapiquí watershed?*** In Chapter 3, I present an approach to *cumulative effects assessment* for the Sarapiquí River system, where little ecological data is available I examine the cumulative effects of hydropower development on the hydrologic connectivity of the Sarapiquí watershed by quantifying effects of eight dams on the watershed's stream network and on downstream hydrology. In addition, I predicted further losses in connectivity that will result from the construction of a proposed hydropower project on the mainstem Sarapiquí River. This chapter also considers other human activities that also affect rivers in the watershed and discusses the possible interactive effects of these activities with hydropower development.

Question 3: ***What are the ecological effects of a diversion dam on a neotropical stream?*** In Chapter 4, I examine the effects of the Doña Julia Hydroelectric Center on fish assemblages and aquatic habitat in the upper Puerto Viejo River, a tributary of the Sarapiquí River. The Doña Julia project is one of ~28 small water diversion dams in Costa Rica. To my knowledge, this study is one of the first in Costa Rica, and perhaps Central America, to investigate the ecological impacts of a diversion dam during operation.

Question 4: ***How important is the Sarapiquí River to human communities?*** In Chapter 5, I consider multiple human uses of rivers in the Sarapiquí watershed—including recreation, transportation, tourism, water supply, irrigation, fishing, and hydroelectricity. I also discuss the role of rivers as *common pool resources* (Hardin 1968; Ostrom 2002) and relate how the Sarapiquí River is a source of cultural identity for long-term residents of the region. Furthermore, I examine local responses of human communities to rapid hydropower development and the subsequent emergence of socio-environmental conflicts in the Sarapiquí watershed.

The material contained in this dissertation represents a case study of hydropower development in Sarapiquí, Costa Rica. However, much of the information and the methodology described here may be applicable to other watersheds in tropical, developing countries. My hope is that the information presented here will be useful to hydropower developers, conservationists, and local residents in Sarapiquí and other parts of the world facing similar development situations.

Literature Cited

Dynesius, M. and Nilsson, C. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266:753-762.

Gleick, P.H. 1992. Environmental consequences of hydroelectric development: the role of facility size and type. Energy 17(8):735-747

Goldsmith, E. and Hildyard, N. 1984. The social and environmental effects of large dams. Wadbridge Ecological Centre, Camelford. 2 volumes.

Graf, W.L. 1999. Dam nation: A geographic census of large American dams and their hydrologic impacts. Water Resources Research 35:1305-1311.

Hardin, G. 1968. The tragedy of the commons. Science 162: 1243-1248.

Laidlaw, K.L. 1996. The implementation of a volunteer stream monitoring program in Costa Rica. Master's thesis, University of Georgia. Athens, GA.

Ostrom, E. (ed). 2002. The Drama of the Commons. National Academy Press, Washington, DC. 521 p.

Pohlman, S.M. 1998. Towards implementation of community-led conservation in lowland rainforest: the water for life program in Puerto Viejo de Sarapiquí, Costa Rica. Master's thesis, University of Georgia. Athens, GA.

Pringle, C.M. 1999. Changing academic culture: interdisciplinary science-based graduate programs to meet environmental challenges in freshwater ecosystems. Aquatic Conservation: Marine and Freshwater Ecosystems 9:615-620.

Pringle, C.M., Freeman, M.C., and Freeman, B.J. 2000. Regional effects of hydrologic alterations on riverine macrobiota in the new world: tropical-temperate comparisons. BioScience 50(9):807-823.

Rosenberg, D.M., Berkes, F., Bodaly, R.A., Hecky, R.E., Kelly, C.A., and Rudd, J.W.M. 1997. Large-scale impacts of hydroelectric development. Environmental Review 5:27-54.

Vargas, R.J. 1995. History of Municipal Water Resources in Puerto Viejo de Sarapiqui, Costa Rica: A Socio-Political Perspective. Master's thesis, University of Georgia. Athens, GA.

Ward, J.V. and Stanford, J.A. (eds). 1979. The ecology of regulated streams: Proceedings of the first International Symposium on Regulated Streams held in Erie, PA, April 18-20, 1979. Plenum Press, New York. 398 p.

World Commission on Dams (WCD). 2000. Dams and development: A framework for decision-making. (www.damsreport.org).

CHAPTER 2:

AN ECOLOGICAL PERSPECTIVE ON ELECTRICITY PRIVATIZATION AND HYDROPOWER IN CENTRAL AMERICA[1]

[1]Olivas, E.A., Pringle, C.M. To be submitted to River Research and Applications.

Abstract

Hydropower dams are rapidly becoming a pervasive feature in the landscapes of tropical, developing countries. In Central America, many new dams are the result of recent electricity sector reforms that privatized electricity generation. The ecological effects of these dams have not been well-studied, and much of private hydropower development in this region has gone undocumented by scientists and conservationists. In this chapter, we review hydropower trends in Central America and examine the ecological impacts of electricity privatization on rivers in the region. We include a case study from our own research in Costa Rica to illustrate how private dams are fragmenting the Central American landscape and recommend strategies for minimizing negative environmental impacts of private hydropower development on river ecosystems.

Keywords: dams, privatization, conservation, Central America, river ecology, Costa Rica

Introduction

Although the rate of dam building in industrialized nations peaked during the middle of the 20th century, the number of hydropower dams built per year is rapidly multiplying in many tropical, developing countries (WCD 2000). This accelerated hydropower development is partially motivated by increasing demands for electricity and what Rogers (1991) calls a 'crisis of rising expectations.' As globalization continues, residents of the developing world are now demanding more of the commodities (e.g., electricity, computers, televisions, packaged foods) characteristic of industrialized nations. Demands for electricity in many developing countries often exceed the global average (Rogers 1991). Hydropower dams, frequently built with capital and technology from industrialized nations, have emerged as a means of promoting economic development in regions like Latin America. The ecological integrity of freshwater ecosystems may be a casualty of increasing hydropower development as dams transform previously intact tropical rivers into fragmented systems.

Our awareness of the broad-scale impacts of hydropower dams in temperate, industrialized nations has increased in recent decades (Benke 1990, Pringle et al. 2000, WCD 2000). However, alteration of aquatic systems by dams in tropical, developing countries has not been well documented. Benke (1990) quantified the extensive modification of streams by dams in the continental United States and showed that dams have altered more than 98% of an original 5,200,000 kilometers of streams. Comprehensive, broad-scale studies like Benke's are rare or non-existent in most tropical, developing countries where most conservation activities have focused on terrestrial systems. Furthermore, most developing regions lack unified, national river conservation movements like those within the United States (e.g., American Rivers, Issac Walton League; see Pringle et al. 1993). Some countries are fortunate to receive attention from international organizations such as International Rivers Network; however, many conservation issues related to hydropower damming remain undocumented. In regions like Central America that are currently being targeted by hydropower developers, freshwater resource conservation deserves more attention than it has traditionally received.

Within the past two decades, all seven countries within Central America (Belize, Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, and Panama) have passed legislation that partially or totally privatizes electricity generation (ECLAC 1996). One result of these new policies has been an increase in the number of dams, especially on low order, high gradient streams draining forested areas. Hydropower has emerged as a primary user of water in some countries and now competes with other human uses like water supply, navigation, and recreation. The increase in the number of dams and water diversions as a result of electricity privatization could have substantial consequences for Central American rivers, yet ecological effects recent hydropower development has gone relatively undocumented by scientists and conservationists.

The purpose of this paper is to: (1) synthesize trends for hydropower development in Central America; (2) briefly discuss the wave of electricity privatization in Central America and provide a summary of recent legislation; (3) discuss the regional ecological consequences of electricity privatization on river ecosystems; and finally (4) focus on Costa Rica as a case study to illustrate the above points. We conclude with a set of recommendations for minimizing negative effects of electricity privatization on Central American river basins.

Trends of hydropower development in Central America

Topography and precipitation have created a large hydroelectric potential for Central America that is considerably out of proportion with the region's small size. The longitudinal orientation of mountain chains down the isthmus, coupled with large amounts of annual precipitation (more than 5 m annually in some areas), has resulted in hundreds of short, high-gradient streams that drain the region in a dendritic pattern. Many dams in the region utilize the dramatic changes in elevation in mountainous areas, and precipitation-driven discharges, to generate electricity. Hydropower currently represents the most important source of electricity in Central America, accounting for more than 50% of power produced regionally. Dependence on hydropower varies by country; Costa Rica presently leads the region with ~85% of its electricity generated by hydropower plants (EIA 2002).

The approach to hydropower development in Central America has been somewhat different than the approach taken in the US and other parts of the world during the last century, particularly in terms of location and size of dams (Reisner and McDonald 1986; Benke 1990; Graf 1999). For example, in his analysis of damming trends in the US, Benke (1990) concluded that development has been heavily focused on large rivers and that only 42 large river segments longer than 200 km remain unfragmented by dams. Multiple large dams traverse the mainstems of many US rivers (e.g., Colorado, the Mississippi, and the Columbia-Snake Rivers), transforming these systems into a series of lakes connected by river reaches with highly altered flow regimes. Additionally, since the construction of the Hoover Dam, the US has been a pioneer in the construction of mega-dams (e.g., Glen Canyon Dam, Grand Coulee Dam). In contrast, the situation in Central America is quite different. First, Central American rivers are relatively short compared to those that drain the North American landscape—the isthmus' longest river is the Coco River (750 km), forming the border between Honduras and Nicaragua. In comparison, the longest river in the US, the Missouri, flows for 4,130 km. Thus, dams on the mainstems of Central American rivers create smaller river fragments than they would on a river several thousand kilometers long. Second, many large Central American rivers, such as the San Juan River (190 km) and Patuca River (530 km), currently remain undammed.

The largest dam in Central America, in terms of generation capacity, is El Cajon Dam in Honduras. Although this dam is high (>200 m tall), it generates only a fraction of the electricity produced by the mega-dams of the US (Loker 2000). Lack of domestic capital in the public sector, coupled with relatively unstable political, social, and economic conditions may have prevented many Central American governments from engaging in large-scale hydropower development (e.g., multiple dam complexes or construction of very large dams; Reisner and McDonald 1986). Until the 1990s, government-owned institutions were responsible for construction and operation of electricity generation centers. Financing of these facilities often involved large loans from multilateral lending institutions such as the World Bank, the International Development Bank (IDB), or the International Monetary Fund (IMF) (Vaux and Goldman 1990). However, since 1990, private companies have started to play a more active role in hydropower development in Central America.

Recent wave of privatization in Central America

The passage of the Public Utilities Regulatory Policy Act in the US in 1978 spurred a wave of reform and restructuring in energy sectors worldwide (Dunkerley 1995, Raphals 2001). In the US, this act permitted private, independent organizations to generate electricity and, along with the Energy Policy Act passed in 1992, was designed to create a competitive environment that would regulate supply and demand of electricity. Following the example of deregulation set by the US, more than 70 developing countries have opened their power sectors in the past two decades, encouraging private participation through new legislation and economic incentives

(Izaguirre 2000, Raphals 2001). Central American countries provide a case in point: since the late 1980s, all have passed legislation that permits partial or total participation of private interests in electricity generation (Table 2.1). These energy sector reforms were designed to decrease pressures on the governments to meet rising electricity demands and to attract foreign capital.

A general result of electricity privatization (also referred to as electricity sector reform) worldwide has been an increase in the number of electricity generation centers (Raphals 2001). Although privatization has strongly favored thermoelectric generation in many countries, it has resulted in an increase in the number of dams in those regions that are rich in freshwater resources, such as Latin America (ECLAC 1996, WCD 2000, EIA 2002). Privatization in developing countries manifests itself through two main strategies: (1) partial or total opening of the power sector to private participation; or (2) allowing private companies to build independent power projects (IPPs) (Dunkerley 1995). In addition, electricity privatization may also involve the sale of government-owned plants to private companies.

Ecological consequences of privatization for freshwater systems

These different privatization strategies will likely result in distinct types of development with unique impacts on environmental systems in Central America. Here, we discuss the ecological consequences of each of these strategies.

The strategy of partial or total opening of the electricity sector to private interests has resulted in the construction of more small generation facilities (e.g., diversion dams) that form part of national electricity networks. In many parts of Central America, electricity privatization has encouraged the construction of multiple small, (<15 m high; <20 MW installed generation capacity) private dams on 2nd to 4th order streams in mountainous regions. These dams appear to be heavily concentrated in areas characterized by high gradients and large amounts of precipitation, such as the mountains of the Central Volcanic Corridor in Costa Rica and the Sierra de las Minas in Guatemala. In Costa Rica, most private dams operate as diversion dams, where the majority (often 90-95%) of a river's discharge is diverted from the stream and returned to the river several km downstream. The 'de-watering' of rivers associated with diversion dams decreases the quantity and quality of habitat for aquatic biota and may facilitate the establishment of exotic riparian or stream-dwelling species (Gleick 1992, Marchetti and Moyle 2001). Stream de-watering may also impact the subterranean water flows characteristic of the volcanic regions of Central America; alteration of recharge patterns in de-watered reaches at high or middle elevations could decrease delivery of water to springs at lower elevations (Pringle and Triska 2000).

The location of small private dams on low-order or headwater streams, and the subsequent losses in hydrologic connectivity, could disrupt ecosystem processes such as nutrient cycling and downstream transport of sediment and organic matter (Ward and Stanford 1983, Peterson et al. 2001). In addition, headwater dams block upstream access of migratory biota to spawning sites or habitat (Pringle 1997, Meyer and Wallace 2001) and can disrupt downstream drift or dispersal of plants and animals (Benstead et al. 1999, Nilsson and Berggren 2000). The concentration of private dams on tributaries, or branch points, of drainages in Central America rather than on main channels, or trunk streams, results in small, isolated stream fragments that are discontinuous with the rest of the watershed. In contrast, if multiple dams were constructed on the main channel, additional dams would most likely break the trunk channel up into more equally sized fragments (Fagan 2002). The damming of tributary streams could isolate populations of aquatic biota; ecological impacts of this development scenario could be especially adverse if a source population (e.g., of fish, aquatic insects, or freshwater shrimp) were located in one of the fragments, with the dam hindering dispersal of individuals to other parts of the watershed (Pulliam 1988, Fagan 2002). Furthermore, in both temperate and tropical systems, there is great uncertainty about the potential cumulative ecological effects of multiple dams on branch / headwater streams and consequent ecological effects on both local and regional scales. Because Central American streams are short (often <100 km), losses in hydrologic connectivity and extensive fragmentation resulting from the operation of multiple small dams may be more severe than they would be in a region with longer mainland rivers.

The construction of larger Independent Power Projects (IPPs) is a potential option at lower elevations in Central America and may result in the construction of large dams. An IPP is generally a large generation project that usually requires substantial investment of private foreign capital in developing countries. In addition, IPPs could be located in large, relatively undisturbed areas and involve different stakeholders, including indigenous groups, governments, conservationists, and foreign dam companies.

Several IPPs have been proposed for Central America. Many of them are large dams; well-known examples include a series of dams on the Patuca River in central Honduras and the Boruca Dam in southern Costa Rica. The ecological impacts of large dams have been studied in both tropical and temperate regions (Rosenberg et al. 1997, Pringle et al. 2000, WCD 2000, Khagram 2003). Three major potential impacts of large dams in Central America are: (1) emission of greenhouse gases from reservoirs; (2) impacts on downstream areas; and (3) loss of biological integrity and extirpation of biota (Rosenberg et al. 1997). For example, the planned construction of the Boruca Dam on the Rio Grande de Terraba in southern Costa Rica is proposed for a river with a high sediment load in a region characterized by landslides. The dam will flood hundreds of hectares of forest, most likely resulting in emissions of methane and carbon dioxide from the decomposing vegetation (Reisner and McDonald 1986). Dams planned for the Patuca River in the Mosquita region of Honduras also illustrate the severity of potential impacts: these developments will fragment one of the largest areas of tropical rainforest north of the Amazon. The Patuca dam series may also endanger several protected reserves (e.g., Rio Platano Biosphere Reserve, Tawahka Indigenous Reserve) that border proposed dam construction sites by opening access to previously remote areas (Gutman 1998).

Costa Rica: a case study of links between electricity privatization and river fragmentation

Hundreds of rivers drain the Costa Rican landscape, creating a large hydropower potential for this small country (51,000 km^2). Hydropower currently accounts for ~85% of domestically-produced electricity for the country's 4 million inhabitants. The national electrification system consists of 10 medium to large sized dams (>15 m high) and an increasing number of smaller dams (<15 m high; <20 MW). Costa Rica's largest dams are the Arenal Dam on the Arenal River, the Corobici Dam on the Santa Rosa River and the Angostura Dam Complex on the Reventazon River, all with installed generating capacities of approximately 170 MW. Smaller dams located on the tributaries of major rivers also contribute to national electrification, especially during peak hours of domestic electricity demand. Other sources of electricity for Costa Rica outside of hydropower include thermoelectric, geothermic, and wind generation.

Before 1990, state-owned utilities, primarily the Costa Rican Institute of Electricity (ICE), were responsible for electricity generation. Increases in the demand for electricity in the late 1980s, combined with a lack of capital in the public sector, led Costa Rica to explore other options to meet energy needs. Electricity sector reforms were introduced in 1990 as a way of decreasing pressures on the ICE by allowing partial participation of private companies in electricity generation. With the average yearly demand for electricity increasing at a rate of ~6%, Costa Rica must add approximately 80 MW annually to its overall installed capacity in order to meet these demands (Mario Alvarado, ACOPE, personal communication).

Electricity sector reform in Costa Rica has been more gradual than in some of the other Central American countries, particularly because of the limits that current legislation places on private involvement in electricity generation. In Costa Rica, two laws passed in 1990 (Law 7200) and 1995 (Law 7508), permit private individuals or organizations to generate electricity. The laws require that all private enterprises establish a contract with the ICE prior to construction of the generation center and maintain the ICE's authority over regulation, transmission, and distribution of electricity. Environmental impact assessments must be completed and approved by the national environmental secretary prior to the granting of contracts for all generation centers larger than two megawatts. Additionally, the laws limit the size (measured by installed capacity) of generation facilities to 20 MW. Furthermore, the total amount of electricity generated by private companies is restricted to 15% of total domestic electricity production.

Despite these limitations to electricity sector reform, impacts of private involvement in electricity generation are evident throughout Costa Rica. Hydropower has been a primary beneficiary of electricity privatization, as evidenced by the construction of 28 small private dams in Costa Rica since 1990 (Figure 2.2). One half of the country's 34 major watersheds now either have operational private hydropower dams or have been targeted for future private hydropower development. Many private hydropower dams operate as diversion dams and are concentrated on gradient breaks in regions with very wet climates. For example, certain watersheds, such as the San Carlos River and Sarapiquí River on the northern Caribbean slope, contain multiple private dams on tributary streams. Many areas in both of these watersheds receive more than four meters of annual rainfall and are characterized by dramatic changes in elevation over short distances. Thus far, only limited efforts have been made to investigate the potential cumulative effects of multiple private diversion dams on these watersheds, and Costa Rican law does not currently limit the number of private generation facilities that can be constructed on a single watershed.

Recommended conservation strategies

The transformations of river ecosystems that have resulted from electricity privatization in Central America illustrate the broad scale impacts of legislation on the environment. Conservation of the region's freshwater biodiversity will depend on more careful consideration of current policies and a more holistic approach to watershed development. In light of current development trends, we present three recommendations to minimize the potential negative environmental impacts of electricity privatization on freshwater ecosystems:

(1) Designate certain watersheds as 'pristine.' Private hydropower development should be encouraged in suburban watersheds rather than in watersheds in rural areas. Prohibiting the construction of dams on the mainstem or tributaries of designated rivers would help to limit the number of watersheds affected by hydropower development. Attempts to declare rivers as 'Natural Historic Monuments' have already been made in watersheds in Costa Rica in response to accelerated hydropower development (see chapter 5 of this dissertation).

(2) Require cumulative effects assessments when more than one dam is built on a watershed. Possible additive or interactive effects of multiple dams on individual rivers or watersheds are often neglected by environmental impact assessments. Impacts of multiple dams on hydrology, fish and shrimp migrations, and municipal water supplies should all be considered in cumulative impact analyses. Cumulative effects assessments are poor in the US but have not been completed at all in many parts of Central America currently undergoing hydropower development.

(3) Develop instream flow methods for Central American streams. Create legislation to enforce instream flow regulations. A survey by Scatena (2004) that included three Central American countries indicated a lack of regionally-based methodology for determining instream flows in river reaches downstream from dams and other withdrawals. More research is needed to determine the flow needs of aquatic biota to develop adequate instream flow methodologies for rivers in the region. There is considerable interest in this field (Scatena 2004) and in 2003 the ICE began organizing a series of workshops in Costa Rica to stimulate public discussion and identify research needs related to instream flows. These workshops involve a variety of stakeholders: conservationists, the ICE, private hydropower developers, the government, scientists, and national and international universities. This is a step in the right direction towards better management and conservation of freshwater resources amidst rapid hydropower development.

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Literature Cited

Benke AC. 1990. A perspective on America's vanishing streams. Journal of the North American Benthological Society 9:77-88.

Benstead JP, March JG, Pringle CM, and Scatena FN. 1999. Effects of a low-head dam and water abstraction on migratory tropical stream biota. Ecological Applications 9:656-668.

Dunkerley J. 1995. Financing the energy sector in developing countries. Energy Policy 23:929-939.

Economic Commission for Latin America and the Caribbean (ECLAC). 1996. Progress in the privatization of water-related public services: A country by country review for Mexico, Central America, and the Caribbean. ECLAC: Environment and Development Division.

Energy Information Administration (EIA). 2002. Regional Indicators: Central America. (www.eia.doe.gov/emeu/cabs/centamenv.htm)

Fagan WF. 2002. Connectivity, fragmentation, and extinction risk in dendritic metapopulations. Ecology 83:3243-3249.

Gleick P. 1992. Environmental consequences of hydroelectric development: The role of facility size and type. Energy 17:735-747.

Goodland RJA, Juras A, Pachauri R. 1993. Can hydro-reservoirs in tropical moist forests be environmentally sustainable? Environmental Conservation 20:122-130.

Gutman WE. 1998. Cry me a river: The Rio Patuca hydroelectric project—boon or bane? Honduras This Week.

Graf WL. 1999. Dam nation: A geographic census of large American dams and their hydrologic impacts. Water Resources Research 35:1305-1311.

Izaguirre AK. 2000. Private participation in energy. The World Bank Group: Private Sector and Infrastructure Network. Note No. 208.

Khagram S. 2003. Temples or tombs? An analysis of large dams. Environment 45:28-37.

Loker WM. 2000. Sowing discord, planting doubts: Rhetoric and reality in an environment and development project in Honduras. Human Organization 59:300-310.

Marchetti MP and Moyle PB. 2001. Effects of flow regime on fish assemblages in a regulated California stream. Ecological Applications 11:530-539.

Meyer JL and Wallace JB. 2001. Lost linkages and lotic ecology: Rediscovering small streams. Pages 295-317 in Press MC, Huntly N, and Levin S, eds. Ecology: Achievement and Challenge. Oxford, UK: Blackwell Science.

Nilsson C and Berggren K. 2000. Alterations of riparian ecosystems caused by river regulation. BioScience 50:783-792.

Peterson BJ et al. 2001. Stream processes alter the amount and form of nitrogen exported from small watersheds. Science 292:86-89.

Pringle CM. 1997. Exploring how disturbance is transmitted upstream: Going against the flow. Journal of the North American Benthological Society 16:425-438.

Pringle CM, Rabeni CF, Benke AC, and Aumen N. 1993. The role of aquatic science in freshwater conservation; cooperation between the North American Benthological Society and Organization for Conservation and Resource Management. Journal of the North American Benthological Society 12:177-184.

Pringle CM and Triska FJ. 2000. Emergent biological patterns and surface-subsurface interactions at landscape scales. Pages 167-193 in Jones JB and Mulholland PJ, eds. Streams and Ground Waters. Academic Press.

Pringle CM, Freeman MC, and Freeman BJ. 2000. Regional effects of hydrologic alterations on riverine macrobiota in the new world: tropical-temperate comparisons. BioScience 50:807-823.

Pulliam HR 1988. Sources, sinks, and population regulation. American Naturalist 132:652-661.

Raphals P. 2001. Restructured rivers: Hydropower in the era of competitive markets. Berkeley, CA: International Rivers Network.

Reisner M. and McDonald RH. 1986. The high costs of high dams. Pages 270-307 in Maguire A and Brown JW, eds. Bordering on Trouble. Adler & Adler, MD for World Resources Institute.

Rogers P. 1991. Energy use in the developing world: A crisis of rising expectations. Environmental Science and Technology 25:580-583.

Rosenberg DM, Berkes F, Bodaly RA, Hecky RE, Kelly CA, and Rudd JWM. 1997. Large-scale impacts of hydroelectric development. Environmental Review 5:27-54.

Scatena FN. 2004. A survey of methods for setting the minimum instream flow standards in the Caribbean basin. River Research and Applications 20:127-135.

Vaux PD and Goldman CR. 1990. Dams and development in the tropics: The role of applied ecology. Pages 101-122 in Goodland R, ed. Race to Save the Tropics. Washington DC: Island Press.

Ward JV and Stanford JA. 1983. The serial discontinuity concept of lotic ecosystems. In Fontaine TD and Bartell SM, eds. Dynamics of lotic ecosystems. Ann Arbor Science.

World Commission on Dams (WCD). 2000. Dams and development: A framework for decision-making. (www.damsreport.org).

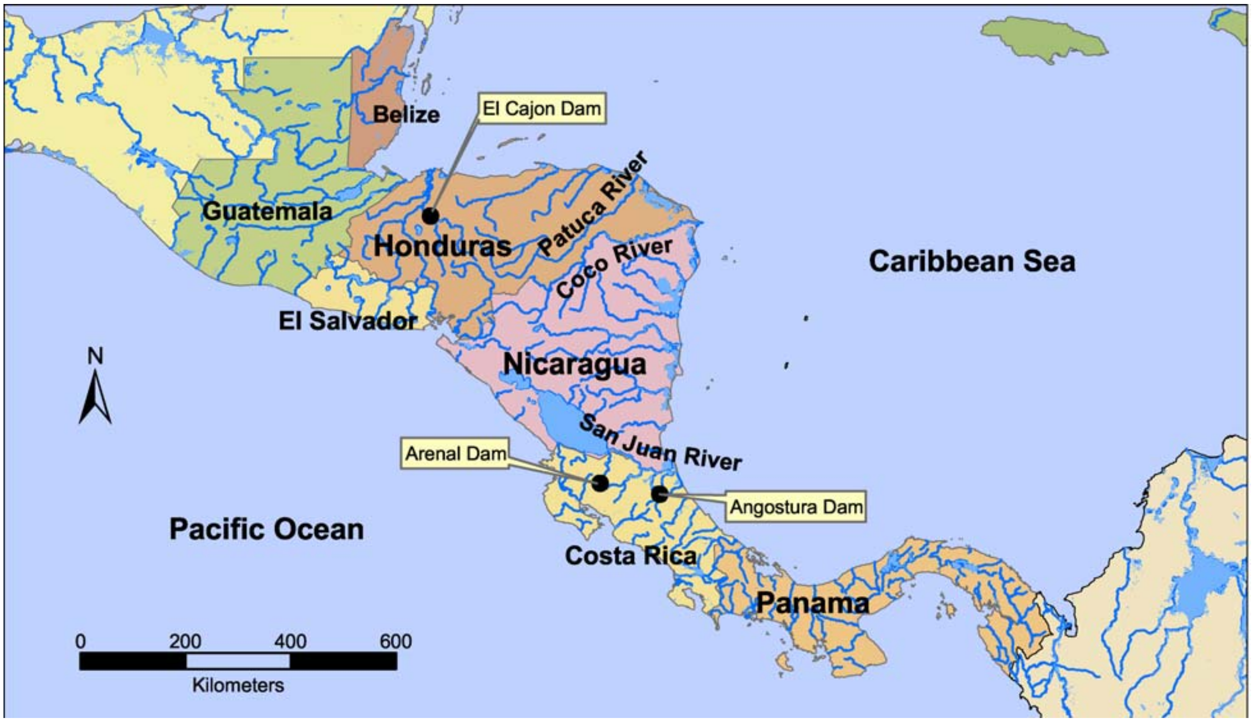

Figure 2.1. The seven Central American countries and major rivers that drain the region. The location of the El Cajon Dam (largest in Central America) and of the two largest dams in Costa Rica is highlighted on the map.

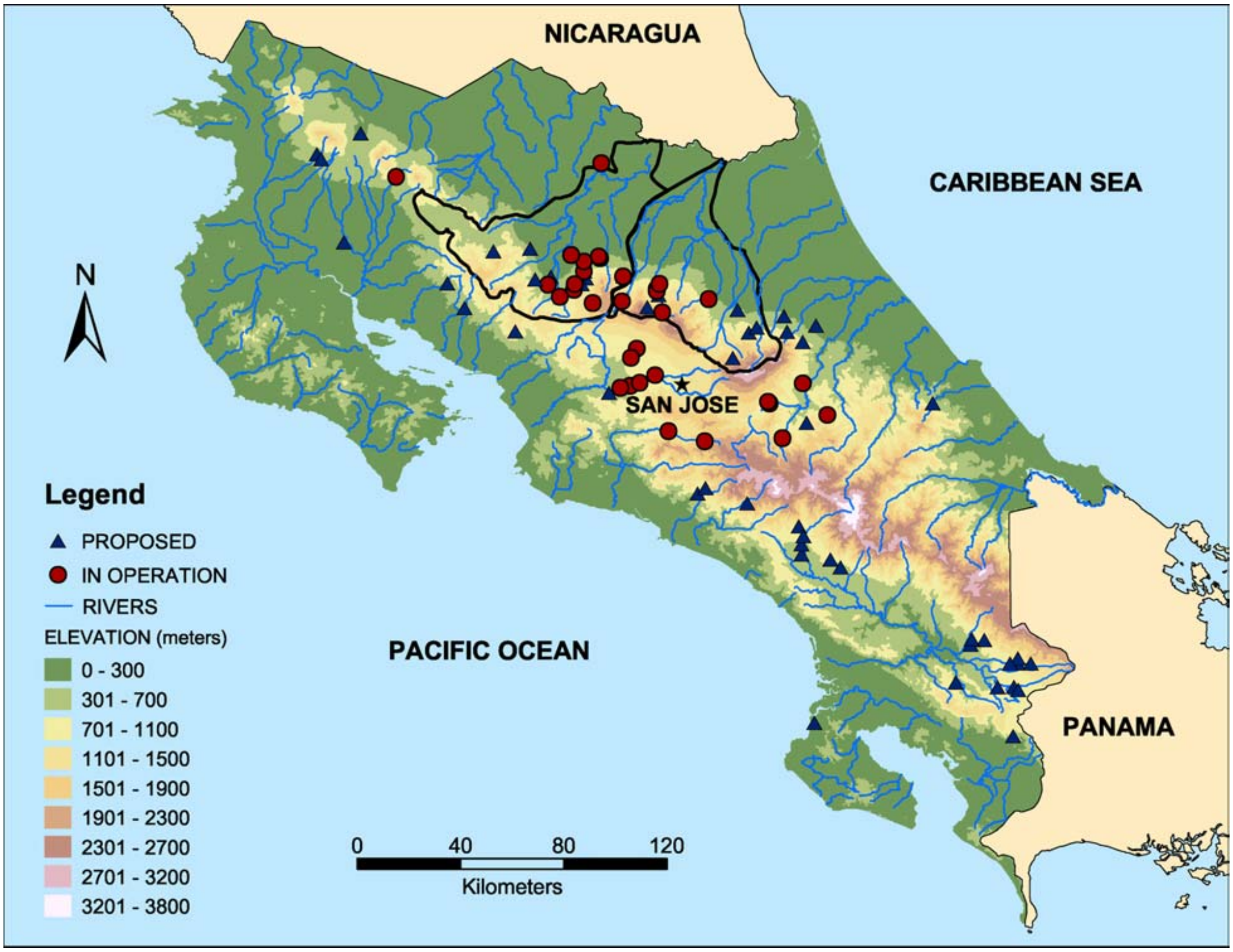

Figure 2.2. Existing and proposed private hydropower projects in Costa Rica. Most projects are located on gradient breaks and dam development has been concentrated on the San Carlos and Sarapiqui watersheds (highlighted on the map).

Table 2.1. Summary of recent legislation related to electricity privatization in Central American countries. Source: Economic Commission for Latin America and the Caribbean (1996); Energy Information Administration (2002).

Country	**Year**	**Legislation**	**Comments**
Belize	1992	Electricity Act of 1992	-privatization of state-owned assets including the electricity company; encourages private participation and competition in energy sector
Guatemala	1986	-Law of Promotion of New and Renewable Sources of Energy	-encouraged private participation in energy production
	1993	-Government Agreement	-offered new opportunities and contracts to private companies
	1995	-additional law	-opened the state-owned national transmission network to other companies; permits buying and selling electricity between the state and private companies; allows contracts between private companies and consumers
El Salvador	1994-95	CEL contracts	-expansion of electricity generation capacity relegated to private companies; additional reforms include private participation in power distribution, possible sales of state-run power plants
Honduras	1994	Marco LAw	-allows private participation in electricity generation and distribution; creates the Electric Cabinet and the National Electric Energy Commission to help with policy making and application
	1996	National Transformation Plan	-intends to attract foreign investments to finance many types of projects, including hydropower dams
Nicaragua	1990	Decree Law 7-90	-created the National Corporation of the Public Sector to oversee privatization of state-owned companies; has led to planned reforms to allow private distribution and generation of electricity, with complete liberalization of generation
Costa Rica	1990	Law 7200	-partial privatization of electricity generation; private companies can contribute 15% of total domestically produced electricity
	1995	Law 7508	-increased amount of foreign capital permitted in electricity generation projects
Panama	1992	Law 16 of 14 July 1992	-created the Coordinating Unity for the Privatization Process to facilitate privatization and oversee sales of state assets
	1995	Law 6 of February 1995	-permits private companies to generate electricity for self consumption or sale; encourages use of renewable resources, specifically hydropower

CHAPTER 3:

PREDICTING CUMULATIVE EFFECTS OF HYDROPOWER DEVELOPMENT ON THE HYDROLOGIC CONNECTIVITY OF A TROPICAL RIVER SYSTEM[1]

[1]Olivas, E.A., Freeman, M.C., and Pringle, C.M. To be submitted to Conservation Biology

Abstract

In Costa Rica, more than 30 hydropower dam projects have been constructed since the early 1990s and watersheds with only one or no dams are becoming rare. While studies of the ecological impacts of individual dams have been limited, there have been no attempts to examine the collective impacts of multiple hydropower dam projects on Costa Rican rivers. As dam construction continues in Costa Rica and other parts of the tropics, cumulative effects assessment will be a necessary tool for conservation and management of freshwater systems. In this study, we showed how simple cumulative effects assessment can be accomplished using limited data. We examined the cumulative effects of multiple hydropower dam projects on the hydrologic connectivity of the Sarapiquí River watershed, Costa Rica. Since 1990, eight hydropower dam projects have been built in the watershed and an additional project, Cariblanco Dam, is under construction. Existing projects have dewatered 31 km of streams in the watershed; the planned Cariblanco Dam will dewater an additional 16 km. Currently, 10 % of total stream km in the watershed is located upstream from dams and are discontinuous with downstream areas; the Cariblanco Dam will increase that number to 14% of total stream km. Although limited data presented a challenge, our results suggested that not all hydropower dam projects are the same and that the placement of dams in the watershed, rather than the total number of dams, is important to preserving hydrologic connectivity. Furthermore, the effects of hydropower dam projects may interact with other human disturbances in the watershed, such as deforestation and increasing fishing pressures, to affect ecological integrity.

Keywords: cumulative effects, dams, hydropower, tropical, streams, fragmentation

Introduction

A major goal of sustainable development worldwide is the integrated management of freshwater resources (Gleick et al. 2002; Postel and Richter 2003). Toward this end, there exists a strong need for comprehensive approaches to assess the impacts of human use of freshwater ecosystems (Bonnell and Storey 2000; Rosenberg et al. 2000; Dube 2003; March et al. 2003). Humans rely heavily on freshwater for potable water and electricity; freshwater resources also provide a variety of ecosystem services, among them waste assimilation, flood control, food sources, and transportation (Postel and Carpenter 1997). Much ecological research has focused on environmental impacts of *individual* human activities on freshwater ecosystems, for instance, the impacts of an individual dam on physical and biological conditions within a river. Conversely, published studies on the *collective* impacts of multiple activities on one system, such as the collective impacts of multiple dams on one river or a watershed, are less common (Rosenberg et al. 2000). Furthermore, while some form of environmental impact assessment is used in most countries, these studies are generally initiated by and restricted to a specific project and conducted over a limited spatial and temporal scale (Burris and Canter 1997; Bonnell and Storey 2000). Potential cumulative effects of multiple human activities on an ecosystem have often been ignored (Burris and Canter 1997; Cooper and Sheate 2002).

The concept of cumulative environmental effects is based on the idea that the impacts of human activities on natural systems are not mutually exclusive of one another. Rather, impacts can be cumulative, and may cause substantial changes to the environment (Beanlands et al. 1986; Preston and Bedford 1988; Bonnell and Storey 2000). Cumulative environmental effects may result from one activity over time or from multiple sources of disturbance over space and time. Ecosystem disturbances may be related, (e.g., multiple water withdrawals on one river) or unrelated (e.g., a dam, an instream mining operation, and a wastewater treatment plant on a segment of river). Cumulative effects of these activities can originate through either additive or interactive processes, or a combination of both. The concept of additive effects refers to a case where cumulative environmental effects can be defined as the sum of the effects of individual disturbances. Alternatively, cumulative environmental effects that result from interactive processes occur when the effect of multiple disturbances is different than the sum of the effects of those disturbances individually (Bonnell and Storey 2000). The practice of cumulative effect assessment is an attempt to systematically evaluate these additive or interacting effects of one or more human influences on an ecosystem (Preston and Bedford 1988; Spaling and Smit 1993; Dubé 2003).

Dams for hydropower, irrigation, or water supply provide examples illustrating the different types of cumulative ecological effects. The concept of additive effects may be explained by studies from the literature describing situations where multiple dams operate on a river. For example, Williams et al. (2001) documented the additive effects of dams on the survival of migratory salmon populations in the Columbia-Snake River system, USA: mortality of smolts increased with the number of dam turbines on the river that smolts had to pass through. The concept of interactive cumulative effects might be explained by a situation where flow reduction below a dam increases fishing effectiveness. In this case, flow reductions and fishing may interact to raise fishing mortality and negatively affect fish populations.

In North America and Europe, watersheds with only one or no dams are rare (Benke 1990; Dynesius and Nilsson 1994). This is also increasingly becoming the case in tropical, developing countries, where dam construction is occurring at an accelerated rate (March et al 2003; WCD 2000). The scientific literature contains several examples of attempts to evaluate cumulative effects of dams on specific parameters (e.g., emission of greenhouse gases, sediment retention, water cycles) on global, regional, and local scales (Table 3.1). Nevertheless, most of these attempts are relatively recent and are far outnumbered by studies on the ecological effects of individual dams (Rosenberg et al. 2000). Well-known attempts to assess cumulative effects of multiple dams include the Serial Discontinuity Concept, proposed by Ward and Stanford (1983), and the Fragmentation Index, presented by Dynesius and Nilsson (1994). However, although these two studies are frequently cited in the literature, published applications of their methods are rare. Perhaps the greatest contribution of these studies is that they articulate the need to address the impacts of river regulation on a broad scale, drawing attention to the magnitude of hydrologic alterations worldwide.

The present study evaluated cumulative effects of hydropower development on the hydrologic connectivity of the Sarapiquí River system, Costa Rica. Hydrologic connectivity is defined here as the flow of energy, matter, and organisms along longitudinal, lateral, vertical, and temporal pathways in a watershed and is essential to maintaining the ecological integrity of a watershed (Ward and Stanford 1989; Pringle 2003). We begin with a detailed description of the study system to document present hydropower development and outline management concerns. We then quantify the cumulative effects of eight existing dams on the connectivity of the stream network and on downstream hydrology. We also predict effects of a proposed dam on connectivity and consider future hydropower development in the watershed. We discuss effects of hydropower development in light of two other recent changes in the Sarapiquí watershed that also affect rivers: deforestation and increased fishing pressures. Our goal is to illustrate the utility of cumulative effects analysis, even in a situation where little data are available for a river system, as is the case in the Sarapiquí watershed.

Study system and management concerns

The Sarapiquí River watershed, Costa Rica, has been targeted for hydropower development for the past 15 years (Figure 3.1). The Sarapiquí River is one of the major confluents of the San Juan River and drains part of the northern Caribbean slope of Costa Rica. Elevational changes greater than 100 m/km characterize the upper watershed, where the 4-8 m of rainfall received annually is more evenly distributed throughout the year than in other parts of Costa Rica (Sanford et al. 1994). The combination of high relief and heavy precipitation has created a large hydropower potential. During the 1990s, eight hydropower projects were built on the Sarapiquí River and its tributaries (Figure 3.2). The majority of these projects are operated by private companies, except for two projects on the Toro River that are run by the Costa Rican Institute of Electricity (ICE), a government-owned institution. Collectively, these hydropower projects (~143 megawatts (MW) generation capacity) account for a little less than 10% of Costa Rica's total installed generation capacity. More dams are currently being planned for the watershed, including the Cariblanco Dam, proposed by the ICE for the mainstem Sarapiquí River. If constructed, the Cariblanco Dam will be the largest dam in the watershed with roughly 80 MW installed capacity. Advanced plans for a third project on the Toro River are also underway at the ICE, as are plans for a 40 MW hydropower project on the General River.

At issue are the impacts of existing and proposed hydropower projects on the ecological integrity of the Sarapiquí river system. Hydropower developments in the Sarapiquí region affect the hydrology and the hydrologic connectivity of the watershed (defined above), with cascading impacts on aquatic biota. In this case, hydrology refers to the natural flow regimes of the Sarapiquí and its tributaries, with emphasis on the annual cycles of high and low discharge events (Poff et al. 1997). Alteration of natural flow regimes by dams in Sarapiquí affects the magnitude and timing of river flows and disrupts natural connections between upstream and downstream reaches (longitudinal connectivity), between channel and floodplain (lateral connectivity), and between channel and groundwater (vertical connectivity).

Primary conservation concerns in the Sarapiquí watershed are that hydropower developments may threaten the survival of native aquatic biota and isolate headwater streams. To date, 44 species of fish have been recorded from the watershed (Bussing 1993; EAO unpublished data); this is probably a conservative estimate since many of the watershed's rivers have never been sampled. Nevertheless, this estimate includes at least two highly mobile fish species, *Joturus pichardi* and *Agonostomus monticola* (Mugilidae) (Cruz 1987; Bussing 1998). It also includes one fish species that is endemic to Costa Rica, *Priapicthys annectens* (Poecilidae), frequently found in headwater streams (Bussing 1998). Boulder and cobble substrate in the headwaters and mid-reaches of the watershed also provides important habitat for freshwater shrimp (*Atya spp*. and *Macrobrachium spp.*). In other parts of the tropics, research has shown that dams negatively affect the migratory behavior of these animals (Holmquist et al. 1998; Benstead et al. 1999); this is potentially the case for freshwater shrimp in Sarapiquí as well.

Hydropower development in Sarapiquí involves a variety of stakeholders. To date, there has been limited consensus among these groups on management objectives for the watershed. Private hydropower companies and the ICE recognize the vast hydropower potential of the Sarapiquí (>300 MW) and want to exploit the watershed's resources to the fullest extent possible. Management concerns for hydropower producers include maintaining forest cover in the upper parts of the watershed to minimize suspended sediments in river reaches above dams. Unnatural increases in sediment that result from land clearing can damage a project's machinery and decrease hydropower production. At present, protected areas, including the vast Braulio Carrillo National Park (~47,000 km^2), maintain roughly one-third of the watershed in natural forest cover. Maintenance of forested areas is also a primary management concern of other stakeholders in Sarapiquí, especially municipal water users and those involved with the region's tourism industry. Potable water for several towns comes from groundwater springs and streams that drain the interior of the national park (Vargas 1995). Additionally, the national park and other protected areas are a hotspot for biodiversity, attracting thousands of international tourists and scientists annually.

Another important management objective of municipal water users, the tourism industry, and local residents of Sarapiquí is maintaining adequate river flows for human uses and for fish habitat. Municipal water users express concern that operation of existing and proposed hydropower projects will negatively affect potable water supplies since they dam and divert water from reaches of river that may be in areas of groundwater recharge (S. Barrantes, Aqueduct of Horquetas, personal communication; Pringle and Triska 2000). Local residents worry that the flow reductions and barriers imposed by the hydropower projects, especially the planned Cariblanco project, will result in major fish population declines or local extirpation of migratory fish species like bobo, *Joturus pichardi*, that are used in recreational and subsistence fishing. White-water rafting, a major component of the tourism industry in Sarapiquí, depends heavily on river flows on the mainstem. Rafting companies have expressed concern that alterations to the hydrology of the Sarapiquí by the planned Cariblanco project will destroy their business due to periods of decreased flow that make rafting impossible, or due to unnatural flow fluctuations that make rafting unsafe. Furthermore, local residents and the tourism industry worry that the increasing hydropower development will detract from the scenic beauty of the

Sarapiquí River, by replacing natural wonders like canyons and waterfalls with concrete impoundments and pipelines.

Hydropower project operations and their environmental impacts

All eight projects in the Sarapiquí watershed operate as water diversion dams, a common type of hydropower project that takes advantage of discharge and elevation gradients to generate electricity (Figure 3.3). Despite the fact that diversion dams are found in many areas of Central America and tropical Asia (Majot 1997), their environmental impacts have not been well studied in the tropics. At least five of the dams in the Sarapiquí watershed were obligated by law to complete an environmental impact statement during planning phases. However, comprehensive studies on the ecology of rivers in Sarapiquí are scarce, and research for environmental impact assessment reports included little field data collection. Thus, impacts of dams were often predicted based on limited information; when no data were available, impacts were projected based on other studies on dams. The same company prepared the environmental impact statements for three hydropower projects in Sarapiquí. Although each of the three projects is located on a different river and one at a lower elevation, the three separate reports contain several identical sections explaining probable environmental impacts of the dams (E. Olivas, personal observation). The system of environmental impact assessment used for hydropower in Sarapiquí is confounded by additional serious problems. For instance, the impacts of each hydropower project were evaluated individually; no efforts have yet been made to predict or assess the cumulative effects of the eight dams on the watershed. Furthermore, studies on the actual impacts of dam operations are also scarce.

Our personal observations and work in the area provide insight into some of the ecological impacts of hydropower projects in the Sarapiquí watershed. These hydropower projects function as water diversion dams, thus their operation results in the 'de-watering' of the reach of river between the diversion site and the water return site. At several of the projects in Sarapiqui, this 'de-watered' reach carries 5-10% of average annual discharge or less and corresponds to a distance of several river kilometers. Discharge reductions in the de-watered reach have been shown to affect the quantity and quality of habitat for aquatic biota and affect the temperature regime of a river (see Chapter 4 of this dissertation). The presence of a concrete dam at the diversion site disrupts longitudinal riverine connectivity, altering the transport of matter and organisms. Although they are not particularly high (all but one are <15 m), dams in the Sarapiquí watershed impede upstream movement of biota and permit downstream movement over the dam only during high flow events. In addition, these dams most likely isolate upstream populations of fishes and freshwater shrimps that inhabit low order streams. The ecology of river reaches downstream from the turbines and water release is also altered by hydropower project operations: water releases during peak periods of electricity generation can be linked to abrupt changes in discharge and water temperature (see Chapter 4). These unnatural fluctuations affect the stability of aquatic habitat for several kilometers downstream and may alter the composition of biotic assemblages in these reaches by favoring species better adapted to highly dynamic environments.

When referring to hydropower development in the Sarapiquí and San Carlos watersheds, a 1997 State of the Nation report on Costa Rica stressed the need for evaluating cumulative environmental effects of hydropower dams (Estado de la Nación 1998). Several years later, questions about the cumulative effects of the eight operational hydropower projects in the watershed remain unanswered. How many projects can the Sarapiquí watershed support while still maintaining natural ecosystem processes? How do multiple projects affect tropical aquatic biota? Are the impacts of multiple projects on tributary streams greater or less than those of a large dam on the mainstem Sarapiquí? How do dams alter watershed connectivity? More information on the ecological consequences of multiple hydropower projects is needed to help guide decisions made by developers and resource managers about placement and operation of future projects.

Methods

Cumulative effects of multiple projects on connectivity— During 1999-2002, we visited 7 of the 8 existing hydropower projects in the Sarapiquí watershed. The purpose of these visits was to meet with managers to discuss operations and collect data about each hydropower project. At five of these sites, we used a Trimble Navigation Geographic Positioning System (GPS) to record the location of the water diversion site and the water return site (turbine house; Figure 3.3). For two of the projects, Don Pedro and Volcan, the hydropower company provided GPS points, because the steep walls of the river channel made data collection difficult with our GPS. The location of the Rio Segundo project was obtained from the feasibility study on file at the Department of Private Generation at the ICE.

We used ArcGIS 8.2, a commercial Geographic Information Systems (GIS) program from the Environmental Systems Research Institute, Inc. (ESRI, Redlands, CA) and 1:50,000 topographic maps of the Sarapiquí region to develop a digital database of rivers for the watershed. Maps were scanned and geo-referenced and then used as base images to delineate segments of rivers. We then used ArcView 3.2 (ESRI, Redlands, CA) and the *Create Strahler Stream Order Extension* to ordinate all streams in the watershed (Strahler 1952; Lanfear 1990). Coordinates of the water diversion and water return sites of each of the existing hydropower projects were imported into the ArcInfo rivers coverage.

To quantify the cumulative effects of the eight existing projects on the connectivity of the stream network, we used ArcInfo to calculate: (1) the length of the dewatered reach of stream between the water diversion and the water return at each hydropower project; and (2) the total stream length upstream from each dam (water diversion site). We considered the dewatered reach to be a break in connectivity because of the significant reductions in discharge (90-95%) that create different physical conditions than those of upstream and downstream river sections. We considered rivers upstream from dams to be discontinuous in a downstream direction during low and normal flow periods and discontinuous in an upstream direction at all times.

We also used ArcInfo and the rivers coverage to predict effects of the proposed Cariblanco hydropower project on the connectivity of the stream network. The ICE provided coordinates for the planned location of the water diversion dam and water return for the Cariblanco hydropower project; we imported these coordinates into the rivers coverage. We then used ArcInfo to calculate the probable length of the dewatered reach of stream and the total river length upstream from the four proposed dams in the Cariblanco project.

Cumulative effects of multiple projects on downstream hydrology— Daily discharge records from a gauge on the Sarapiquí River near the town of Puerto Viejo were provided by the Department of Hydrology at the ICE for the period 1970-1998. We used these discharge records and the *Indicators of Hydrologic Alteration* (*IHA*) program (Richter et al. 1996) to estimate the cumulative effects of multiple hydropower projects on the downstream hydrology of the Sarapiquí River. The *IHA* program compares daily discharge data collected before and after a river alteration occurs (i.e., dam construction) by calculating values for 33 hydrologic variables (i.e., magnitude, timing, and duration of low and high flow events; seasonality of flows, etc.) for the pre- and post-alteration datasets. The *IHA* then determines whether there are significant differences between datasets for the calculated values of each variable (Richter et al. 1996; Richter et al. 1997). In this study, we divided the available discharge data for the Sarapiquí River into: (1) pre-hydropower development (1970-1990); and (2) post-hydropower development (1990-1998). Between 1990-1998, four hydropower projects began operation on the Sarapiquí River and its tributaries upstream from the gauging station. Because the confluence of the Toro River is downstream from the gauge, the three dams on this subwatershed could not be included in the analysis. Also, although the Doña Julia project on the Puerto Viejo River is upstream from the gauge, this project did not begin full operation until 1999.

Results and Discussion

Cumulative effects of multiple dams on connectivity—A total of 30.9 river kilometers in the Sarapiquí watershed have been dewatered as a result of hydropower dam operations: 5.79 km of 1^{st} and 2^{nd} order streams, and 25.06 km of 3^{rd} order streams (Table 3.3). These 30.9 km now regularly carry between 5-10 % of average annual discharge, except during storms or high flow events. The hydropower project with the longest dewatered reach currently is the Volcan Dam on the Volcan River (Table 3.3).

Extensive stream dewatering has major implications for the hydrologic connectivity, and thus the ecological integrity of the Sarapiquí river system. Hydropower projects in Sarapiquí are designed so that gross static height, GSH (i.e., the difference in elevation between the water diversion site and the turbines), significantly exceeds dam height, DH. While this project design (GSH>DH) has been considered advantageous from an environmental perspective because it can reduce evaporative water losses and sedimentation behind a dam, past research has shown that the destruction of aquatic habitat and subsequent loss of species associated with dewatering may outweigh the environmental benefits of the GSH>DH project design (Gleick 1992). For example, ecological studies in a dewatered stream below a diversion dam in California, USA, showed that dewatering facilitates the replacement of native fishes by introduced species (Marchetti and Moyle 2000; 2001). In the Sarapiquí watershed, a study of fish assemblages in the Puerto Viejo River near the Doña Julia Hydroelectric Center found that 'tolerant' fish species with opportunistic-type life histories (see Winemiller 1995) dominated assemblages in the ~4 km dewatered reach of the river (see Chapter 4 of this dissertation). In the future, exotic species such as tilapia (*Oreochromis spp.*), now cultivated in small ponds throughout the Sarapiquí region, may eventually colonize the altered habitats offered by dewatered reaches downstream from dams. The adaptability of tilapia to a wide range of flow, temperature, and water quality conditions could make these species stronger competitors for food and space in dewatered reaches than native fishes.

Past research on the effects of drought on tropical stream biota suggests that extended low-water periods significantly alter aquatic communities (Covich et al. 2003). A direct result of prolonged drought conditions is the localized crowding of aquatic biota into severely reduced habitat; this crowding may have long-term consequences on survivorship through decreased reproduction or increased predation pressures (Covich et al. 2003). The impacts of stream dewatering on aquatic biota in Sarapiquí may be comparable to, or harsher than, the impacts of a prolonged drought, especially during the months with less precipitation (Feb-May). If maintaining the ecological integrity of the Sarapiquí river system is a management objective of stakeholders in the watershed, appropriate minimum flows should be required downstream from all dams to lessen the negative effects of dewatering on aquatic biota during drier months. These flows should be based on the natural flow regimes of rivers in tropical rainforest biomes.

Aside from effects on hydrologic connectivity, dewatering of streams in Sarapiquí could also have implications for human health. In other parts of the humid tropics, the conversion of lotic environments to more shallow, slow-flow conditions by dams has been linked to the spread of diseases (Jobin 1999). Although most documented cases linking dams and disease are associated with large reservoirs, the vectors of some of these diseases are mosquitoes that can also breed in stagnant or slow-moving river pools. These habitats characterize many of the 30.9 km of dewatered streams in the Sarapiquí river system; however, current information is insufficient for documenting potential links between stream dewatering and spread of mosquito-borne diseases in the region. In general, more scientific research is needed on how vector populations respond to changes in hydrology associated with dams.

In addition to stream dewatering, another result of hydropower development in Sarapiquí is the isolation of headwater systems from the stream network. A total of 306.8 river km are located upstream from dams in Sarapiquí; dams have disrupted the connectivity between these rivers and the rest of the watershed (Table 3.4). These 306.8 km correspond to 10.8 **%** of 1st through 3rd order stream length in the watershed. However, the situation may actually be more serious because our results underestimate the total length of 1st order streams since many headwater, ephemeral, and intermittent streams do not show up on topographic maps at a 1:50,000 scale.

Our results indicate that fragmentation of the Sarapiquí river system by dams is non-random; dams are heavily concentrated on high gradient, 2nd and 3rd order streams above 400 m elevation. This damming of low-order, tributary streams may alter connectivity and affect ecological integrity differently than a case where multiple dams were built on the lower reaches of the mainstem Sarapiqui River (Figure 3.5). Concentration of multiple dams on branch streams divides the network into multiple small, isolated fragments; each additional dam increases the number of small fragments and the number of discontinuous low-order streams. In contrast, dams on the mainstem would break the channel into larger, more equally sized fragments (Fagan 2002). Moreover, the ecological role of headwater or low-order streams in a network is often underestimated, despite the fact that these streams are important sources of sediment, nutrients, and organic matter for downstream areas (Meyer and Wallace 2001; Gomi et al. 2002). Dams on low-order streams can trap as much as 95% of sediment and organic matter (Waters 1995), resulting in sediment-starved, erosive rivers below dams (Ligon et al. 1995). In the Sarapiquí watershed, observations of the Puerto Viejo River below Doña Julia Dam support this claim: after only 3 years of operation, we noted a substantial increase in exposed bedrock below the dam due to sediment trapping (E.Olivas, personal observation). Low-order streams also may provide critical habitat or spawning grounds for freshwater biota and harbor diverse assemblages of aquatic invertebrates. Dams hinder upstream access to these areas and disrupt downstream drift of macroinvertebrates from headwater streams (Pringle 1997; Holmquist et al. 1998; Benstead et al. 1999).

Specifically, what are the consequences of this hydropower development scenario on the ecological integrity of the Sarapiquí river system? How important are the downstream linkages of headwater systems in a tropical catchment? Is the passage of water over dams during storms sufficient to maintain the export of sediment, nutrients, organic matter, and biota to downstream areas? How important is longitudinal connectivity in an upstream direction to maintaining biotic assemblages and ecological processes? As hydropower development continues in Sarapiquí, resource managers need the answers to these questions and scientists working in tropical freshwater systems should strive to provide them.

The proposed Cariblanco hydropower project, expected to begin operation in 2006, will result in further losses in connectivity in the Sarapiquí watershed. The Cariblanco project is the most advanced (in terms of planning) of several additional dam projects proposed for the Sarapiquí river system. The project includes a 13 m high dam on the mainstem Sarapiquí River, as well as smaller dams on 3 more rivers (ICE 2001). When completed, it will dewater an additional 16.12 km of streams: 9.33 km on the Sarapiquí River between the towns of Cariblanco and San Miguel and a total of 6.71 km on the other three rivers. A total of 108.4 river km will be located upstream from the main dam on the Sarapiquí River (Table 3.5). Currently, 9.1% of total stream kilometers in the Sarapiquí watershed are upstream from dams. The operation of the Cariblanco hydropower project will increase this percentage to 13.3% of stream length in the watershed.

The results of our *cumulative effects analysis* of hydropower development (Tables 3.3, 3.4, and 3.5) suggest that the placement of hydropower projects, rather than the total number of dams, may be more important in preserving connectivity in the Sarapiquí river system since not all hydropower projects are the same. For example, in terms of dewatering, there is not always a direct relationship between electricity produced and km of stream dewatered. The Don Pedro, Volcan, and Doña Julia projects all dewater roughly 6-7 km of stream and produce 14, 17, and 18 megawatts (MW) of electricity, respectively. The Toro I and II projects together dewater 6.8 km but in contrast, produce almost five times the electricity of the Don Pedro, Volcan, and Doña Julia projects (Figure 3.6). Thus, the number stream km dewatered per MW of electricity is much lower for the Toro projects combined than for those other three; this is probably because the Toro projects are located in an area of extremely high relief. Similar trends are evident in terms of river km upstream from dams. Again, a comparison of the Toro projects with the Doña Julia project indicates that MW produced is not always correlated with number of river km upstream from a dam (Figure 3.7).

If maintaining the ecological integrity of the watershed is a management concern of the ICE and private hydropower developers, future projects should not be constructed on currently undammed subwatersheds of large tributaries such as the Sucio River, the Poza Azul River, the Peje River, and the Sardinal River (Figure 3.2). Instead, any further hydropower development should be concentrated on already dammed rivers so that some degree of connectivity between headwater and downstream systems can be maintained in the watershed. Plans at the ICE for a third phase of the Toro I and II hydropower projects (known as Toro III), on the Toro River illustrate this idea. The proposed Toro III hydropower project, slated for completion in 2015, will have an installed generation capacity of 50 MW and will operate on an already altered sub-watershed of the Sarapiquí river system.

Cumulative effects of multiple dams on downstream hydrology—Daily discharge records for the Sarapiquí River were only available through 1998, when the river's gauge near the town of Puerto Viejo ceased functioning. No significant differences in hydrologic variables could be detected using the two datasets, 1970-1990 and 1990-1998.

The limited data available for the Sarapiquí watershed present a challenge to analyses of the cumulative effects of hydropower dams on downstream hydrology. Consequently, it is difficult to draw strong conclusions from our results. A model comparing pre- and post-hydropower development conditions using hourly discharge data would have been more useful in our analysis because hydropower projects in Sarapiquí have no long-term (e.g. more than a day) water storage. Hence, these projects have limited ability to influence seasonal flows through storage of water during high flow periods for re-release during low flow months. Although peak releases of water from projects occur twice daily, the time scale of daily discharge data is probably not sensitive enough to detect these fluctuations. As is typical for many rivers in tropical, developing countries, hourly discharge data do not exist for the Sarapiquí River. Our analysis also would have benefited from data in the years following the start of hydropower development; unfortunately these data were also not available. The lack of data and the inconclusive results of our analysis articulate the need for re-installing functional gauges on the Sarapiquí River. In light of present hydropower development trends in the watershed, tributaries of the Sarapiquí should also be gauged.

In addition to effects of multiple dams on downstream hydrology, fluctuations in water temperature as a result of hydropower development on the Sarapiquí and other rivers should be considered in future cumulative effects analyses in the watershed. A study downstream from the Doña Julia project on the Puerto Viejo River showed that water temperature can drop by as much as 4 ºC in less than an hour when water is being released from the turbines (see chapter 4 of this dissertation). These fluctations in water temperature downstream are probably characteristic of areas downstream from other hydropower projects and may affect aquatic biota adapted to more stable thermal conditions.

Further considerations

Hydropower development is usually accompanied by other anthropogenic disturbances in a given watershed. Thus, the cumulative effects of multiple hydropower projects have the potential to interact with the ecological impacts of other human activities. This is clearly the case for the Sarapiquí river system. Less than 50 years ago, the Sarapiquí region was considered one of the last frontier areas of Costa Rica, accessible only by boat or mule track (Butterfield 1994). However, road construction and regional expansion of agriculture during the latter half of the 20^{th} century have now made Sarapiquí one of the most rapidly developing areas of the country. Resulting changes in land use and increases in human population are impacting the ecological integrity of the Sarapiquí watershed. Recent conversion of forest to agricultural lands and increasing fishing pressures in the region merit attention as well, as they have potential to interact with the effects of hydropower dams on the watershed.

Forest conversion—In the mid 1960s, forests covered roughly 70% of the Sarapiquí region (Butterfield 1994). Since then, dramatic changes in land uses have occurred, and today forests cover only about 30% of land area (Table 3.6; Butterfield 1994; Sanchez-Azofeifa and Quesada-Mateo 1995; Read 1999; Sanchez-Azofeifa et al. 1999). Deforestation until the late 1980s was largely conversion of forest to pasture, driven by a burgeoning beef cattle industry (Read 1999; Sanchez-Azofeifa et al.1999). However, since 1990, conversion of forest and abandoned pastures to banana plantations has been a primary driver of land use change in Sarapiquí (Hunter 1994; Vargas 1995; Sanchez-Azofeifa et al. 1999). Pineapple plantations have also expanded considerably over the past decade. Ecologically, landscape alteration for banana and pineapple agriculture is more severe than pasture land uses, due to the excessive erosion of soils and the intensive use of agricultural chemicals (Sanchez-Azofeifa et al. 1999; 2002).

Previous studies have considered the impacts of upstream deforestation and sediment accumulation on hydropower generation in Costa Rica (Sanchez-Azofeifa et al. 2002). However, in Sarapiquí, land cover above dams has either remained unchanged or has been reforested over the past two decades; most deforestation in the watershed is currently occurring downstream from hydropower developments. It is important to consider the location of these two types of disturbances in the watershed and how they may interact to affect the ecological integrity of the Sarapiquí watershed. For example, decreased water quality resulting from deforestation and intensive agricultural practices could force aquatic biota into more forested upstream areas. However, water diversions and peak flows associated with hydropower projects could prevent establishment and survival of aquatic biota in these upstream areas. Forest restoration activities, especially along lowland streams draining agricultural areas, are essential for long-term conservation of the ecological integrity of the Sarapiquí watershed.

Fishing pressures—Since the mid-1970s, the population of Sarapiquí County has grown from around 13,000 to 45,000 inhabitants, largely due to expansion of banana agriculture (Vargas 1995; INEC 2004). Park guards from La Selva Biological Station (located at the confluence of the Puerto Viejo and Sarapiquí Rivers; Figure 3.2) link these increases in human population with the growing amount of illegal fishing that goes on in the watershed (E. Paniagua, La Selva park guard, personal communication). Fishing laws exist for the watershed, permitting a person to catch up to five individual fishes per day with a hook and line during daylight hours. However, these laws are poorly enforced. Instead, many fish in the watershed are caught at night with large nets, spear guns, or by ‘poisoning’ streams with chemicals (Table 3.7). Species most affected by illegal fishing include the bobo (*Joturus pichardi*), machaca (*Brycon guatemalensis*), moga (*Theraps underwoodi*), and guapote (*Parachromis dovii*). Some of these fish, especially the bobo, sell for more than US$7/kg. At that rate, the earnings from the sale of one large fish may exceed the wages garnered by an agricultural worker in one day. Illegal fishing also negatively affects freshwater shrimps (*Atya spp.* and *Macrobrachium spp.*). A detrimental but common method of capturing these animals is to pour agricultural chemicals (e.g., Lacnate) into a stream to flush shrimps out from under rocks.

Increasing human population pressures and widespread illegal fishing may exacerbate the effects of hydropower projects on the ecological integrity of the Sarapiquí River system. For example, the concentration of dams on low-order, tributary streams and the resulting changes in aquatic habitat could force fishes that normally inhabit these areas to move downstream in search of better habitat. However, dense human populations and increased fishing pressures in downstream areas may threaten the long-term persistence of populations of target fish species even more than hydropower development. Likewise, dams may restrict access to upstream refuge areas for fishes, increasing rates of fishing mortality. Again, it is necessary to consider the location of disturbances in the watershed: the interaction between the effects of hydropower development in the headwaters and increased fishing pressures in the mid-reaches and lowlands may pose a major threat to the ecological integrity of the Sarapiquí watershed.

Conclusions

Although data limitations for the Sarapiquí watershed present a challenge to cumulative effects assessment of hydropower development, our results illustrate how simple analyses can be used to predict impacts of human disturbances on the hydrologic connectivity of a river system. This study revealed that roughly one-tenth of stream length in the Sarapiquí watershed is now upstream from dams and 1% of stream km have substantially reduced discharge. In addition, the placement of dams will be a key component of preserving ecological integrity in the face of future hydropower development; future projects should be concentrated on altered streams when possible. Increased losses of connectivity that will result from the Cariblanco Dam illustrate the importance of dam placement. The Cariblanco Dam, if constructed as planned, will result in a 50% increase in upstream km and in dewatered km of river. The methodology presented here may be useful for planning hydropower projects in the future to avoid unnecessary compromises to ecological integrity in Sarapiquí and other river systems.

Perhaps what is currently happening to the Sarapiquí river system is a good example of what Odum (1982) called the ‘tyranny of small decisions.’ In Sarapiquí, the cumulative effects of hydropower projects, forest conversion, and illegal fishing practices are compromising the ecological integrity of the watershed. To an individual developer, the decision to dam and dewater one or two streams may seem ‘rational,’ in light of the potential economic and social benefits of electricity generation. To a rural resident, the decision to cut down a patch of forest to plant crops or exceed the legal limit for the number of fish removed from the river may seem a ‘rational’ way to temporarily improve her/his economic condition. However, as this study indicates, losses in hydrologic connectivity and the cumulative effects of human activities on the watershed provide evidence that an aggregation of these individual, rational decisions can translate into major environmental changes across the landscape. Future conservation of the Sarapiquí watershed will depend on a reversal of the current reductionist approach to environmental impact assessment and management to a more integrated process. It will also depend on a greater desire of rural populations to protect natural resources.

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Literature Cited

Anctil, F. and Couture, R. 1994. Cumulative impacts of hydroelectric development on freshwater levels of Hudson Bay. Canadian Journal of Civil Engineering **21**(2):297-306.

Beanlands, G.E., Erckmann, W.J., Orians, G.H., O'Riordan, J., Policansky, D., Sadar, M.H., and Sadler, B. (eds). 1986. Cumulative environmental effects: a binational perspective. Canadian Environmental Assessment Research Council / U.S. National Research Council, Ottawa, Ontario, and Washington, D.C., 166 pp.

Benke, A.C. 1990. A perspective on America's vanishing streams. Journal of the North American Benthological Society **9**:77-88.

Benstead J.P., March J.G., Pringle C.M., and Scatena F.N. 1999. Effects of a low-head dam and water abstraction on migratory tropical stream biota. Ecological Applications **9**:656-668.

Bonnell, S. and Storey, K. 2000. Addressing cumulative effects through strategic environmental assessment: A case study of small hydro development in Newfoundland, Canada. Journal of Environmental Assessment Policy and Management **2**:477-499.

Burris, R.K. and Canter, L.W. 1997. Cumulative impacts are not properly addressed in environmental assessments. Environmental Impact Assessment Review **17**:5-18.

Bussing, W.A. 1993. Fish communities and environmental characteristics of a tropical rain forest river in Costa Rica. Revista de Biologia Tropical **41**:791-809.

Bussing, W.A. 1998. Peces de las Aguas Continentales de Costa Rica. Editorial de la Universidad de Costa Rica, San Jose.

Butterfield, R.P. 1994. The regional context: Land colonization and conservation in Sarapiqui. Pages 299-306 in McDade, L.A., Bawa, K.S., Hespenheide, H.A., and Hartshorn, G.A. La Selva: Ecology and Natural History of a Neotropical Rain Forest. University of Chicago Press, Chicago.

Cooper, L.M. and Sheate, W.R. 2002. Cumulative effects assessment: A review of UK environmental impact statements. Environmental Impact Assessment Review **22**:415-439.

Covich, A.P., Crowl, T.A., and Scatena, F.N. 2003. Effects of extreme low flows on freshwater shrimps in a perennial stream. Freshwater Biology **48**:1199-1206.

Cruz, G.A. 1987. Reproductive biology and feeding habitats of cuyamel, *Joturus pichardi*, and tepemechin, *Agonostomus monticola* (Pisces:Mugilidae) from Rio Platano, Mosquitia, Honduras. Bulletin of Marine Science **40**:63-72.

Dube, M.G. 2003. Cumulative effect assessment in Canada: A regional framework for aquatic ecosystems. Environmental Impact Assessment Review **23**:723-745.

Dynesius, M. and Nilsson, C. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science **266**:753-762.

Estado de la Nación (Costa Rica). 1998. Estado de la Nación en Desarrollo Humano Sostenible. San Jose, Costa Rica. Informe 4.

Fagan, W.F. 2002. Connectivity, fragmentation, and extinction risk in dendritic metapopulations. Ecology **83**(12):3243-3249.

Gleick, P.H. 1992. Environmental consequences of hydroelectric development: the role of facility size and type. Energy **17**(8):735-747

Gleick, P.H., Burns, W.C., Chalecki, E.L, Cohen, M., Cushing, K.K., Mann, A., Reyes, R. Wolff, G.A., and Wong, A.K. 2002. The World's Water 2002-2003. Island Press, Washington, DC.

Gomi, T., Sidle, R.C., and Richardson, J.S. 2002. Understanding processes and downstream linkages of headwater systems. BioScience **52**(10):905-916.

Holmquist, J.G., Scmidt-Gengenbach, J.M., and Yoshioka, B.B. 1998. High dams and marine-freshwater linkages: effects on native and introduced fauna in the Caribbean. Conservation Biology **12**(3):621-630.

Hunter, J.R. 1994. Is Costa Rica truly conservation-minded? Conservation Biology **8**:592-595.

Instituto Nacional de Estadisticas y Censos (INEC). 2004. Results of the IX National Census for Costa Rica. www.inec.go.cr.

Jobin, W.R. 1999. Dams and Disease: Ecological Design and Health Impacts of Large Dams, Canals, and Irrigation Systems. Routledge, New York. 584 pp.

Knighton, D. 1984. Fluvial Forms and Processes. Edward Arnold, London.

Lanfear, K.J. 1990. A fast algorithm for automatically computing Strahler stream order. Water Resources Bulletin **26**(6):977-981.

Ligon, F.K., Dietrich, W.E., and Trush, W.J. 1995. Downstream ecological effects of dams: a geomorphic perspective. BioScience **45**(3):183-192.

Majot, J. (ed). 1997. Beyond Big Dams: A New Approach to Energy Sector and Watershed Planning. International Rivers Network publication.

March, J.G., Benstead, J.P., Pringle, C.M., and Scatena, F.N. 2003. Damming tropical island streams: problems, solutions, and alternatives. BioScience **53**:1069-1078.

Marchetti, M.P. and Moyle, P.B. 2000. Spatial and temporal ecology of native and introduced fish larvae in lower Putah Creek, California. Environmental Biology of Fishes **58**:75-87.

Marchetti, M.P. and Moyle, P.B. 2001. Effects of flow regime on fish assemblages in a regulated California stream. Ecological Applications **11**(2):530-539.

Meyer, J.L. and Wallace, J.B. 2001. Lost linkages and lotic ecology: rediscovering small streams. Pages 295-317 in Press, M.C., Huntly, N.J., Levin, S. (eds.). Ecology: Achievement and Challenge. Blackwell Scientific, Oxford, UK.

Odum, H.T. 1982. Environmental degradation and the tyranny of small decisions. BioScience **32**(9):728-729.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C. 1997. The natural flow regime. BioScience **47**:769-784.

Postel, S. and Carpenter, S. 1997. Freshwater ecosystem services. In Daily, G.C., Reichert, J.S., and Meyers, J.P. (eds). Nature's Services: Societal Dependence on Natural Systems. Island Press, 412 pp.

Postel, S. and Richter, B.D. 2003. Rivers for Life: Managing Water for People and Nature. Island Press, 264 pp.

Preston, E.M. and Bedford, B.L. 1988. Evaluating cumulative effects on wetland functions: a conceptual overview and generic framework. Environmental Management **12**(5):565-583.

Pringle, C.M. 1997. Exploring how disturbance is transmitted upstream: going against the flow. Journal of the North American Benthological Society **16**:425-438.

Pringle, C.M. 2003. What is hydrologic connectivity and why is it ecologically important? Hydrological processes **17**:2685-2689.

Pringle C.M. and Triska F.J. 2000. Emergent biological patterns and surface-subsurface interactions at landscape scales. Pages 167-193 in Jones JB and Mulholland PJ, eds. Streams and Ground Waters. Academic Press.

Pringle, C.M., Freeman, M.C., and Freeman, B.J. 2000. Regional effects of hydrologic alterations on riverine macrobiota in the new world: tropical-temperate comparisons. BioScience **50**(9):807-823.

Read, J.A. 1999. Land-cover change detection for the tropics using remote sensing and geographic information systems. Dissertation. Louisiana State University.

Richter, B.D, Baumgartner, J.V., Wigington, R., and Braun, D.P. 1996. How much water does a river need? Freshwater Biology **37**:231-249.

Richter, B.D, Baumgartner, J.V., Powell, J., and Braun, D.P. 1997. A method for assessing hydrologic alteration within ecosystems. Conservation Biology **10**(4):1163-1174.

Rosenberg, D.M., Berkes, F., Bodaly, R.A., Hecky, R.E., Kelly, C.A., and Rudd, J.W.M. 1997. Large-scale impacts of hydroelectric development. Environmental Review **5**:27-54.

Rosenberg, D.M., McCully, P., and Pringle, C.M. 2000. Global-scale environmental effects of hydrological alterations: introduction. BioScience **50**(9):746-751.

Sanchez-Azofeifa, G.A. and Quesada-Mateo, C.A. 1995. Deforestation, carbon dynamics, and sustainable mitigation measures in Costa Rica: the Puerto Viejo de Sarapiqui case study. Interciencia **20**:396-400.

Sanchez-Azofeifa, G.A., Harriss, R.C., Storrier, A.L., and de Camino-Beck, T. 2002. Water resources and regional land cover change in Costa Rica: impacts and economics. International Journal of Water Resources Development **18**(3):409-424.

Sanchez-Azofeifa, G.A., Quesada-Mateo, C., Gonzalez-Quesada, P., Dayanandan, S., and Bawa, K.S. 1999. Protected areas and conservation of biodiversity in the tropics. Conservation Biology **13**(2):407-11.

Sanford, R.L., Paaby, P., Luvall, J.C., and Phillips, E. 1994. Climate, Geomorphology, and Aquatic Systems. Pages 19-33 in McDade, L.A., Bawa, K.S., Hespenheide, H.A., and Hartshorn, G.A. La Selva: Ecology and Natural History of a Neotropical Rain Forest. University of Chicago Press, Chicago.

Spaling, H. and Smit, B. 1993. Cumulative environmental change: Conceptual frameworks, evaluation approaches, and institutional perspectives. Environmental Management **17**(5):587-600.

St. Louis, V.L., Kelly, C.A., Duchemin, E., Rudd, J.W.M., and Rosenberg, D.M. 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. BioScience **50**(9):766-775.

Strahler, A.N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Bulletin of the Geological Society of America **63**:1117-42.

Vargas, R.J. 1995. History of Municipal Water Resources in Puerto Viejo de Sarapiqui, Costa Rica: A Socio-Political Perspective. Master's thesis, University of Georgia. Athens, GA.

Vorosmarty, C.J., Sharma, K.P., Fekete, B.M., Copeland, A.H., Holden, J., Marble, J., and Lough, J.A. 1997. The storage and aging of continental runoff in large reservoir systems of the world. Ambio **26**:210-219.

Vorosmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P., and Syvitski, J.P.M. 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. Global and Planetary Change **39**(1-2):169-190.

Ward, J.V. and Stanford, J.A. 1983. The serial discontinuity concept of lotic ecosystems. Pages 29-42 in Fontaine, T.D. and Bartell, S.M. (Eds.), Dynamics of Lotic Ecosystems. Ann Arbor Science, Ann Arbor.

Ward, J.V. and Stanford, J.A. 1989. The four-dimensional nature of lotic ecosystems. Journal of the North American Benthological Society **8**:2-8.

Waters, T.F. 1995. Sediment in Streams; Sources, Biological Effects, and Control. American Fisheries Society, Bethesda, MD. 251 pp.

Williams, J.G., Smith, S.G., and Miur, W.D. 2001. Survival estimates for downstream migrant yearling juvenile salmonids through the Snake and Columbia rivers hydropower system, 1966-1980 and 1993-1999. North American Journal of Fisheries Management **21**(2):310-317.

Winemiller, K.O. 1995. Aspects structurels et fonctionnels de la biodiversite des peuplements de poissons. Bulletin Francais du Peche et Pisciculture **339**, 23-45.

World Commission on Dams (WCD). 2000. Dams and Development: A Framework for Decision-Making. www.dams.org.

Table 3.1. Selected examples from the scientific literature of attempts to analyze cumulative effects of dams.

Scale	References	Study description
Global	St. Louis et al. 2000	Estimated global emission of greenhouse gases from reservoirs.
	Vorosmarty et al. 1997	Estimated global aging of river runoff based on water storage in reservoirs.
	Vorosmarty et al. 2003	Estimated global impact of large reservoirs on riverine sediment transport to oceans.
	Dynesius and Nilsson 1994	Calculated percent fragmentation by dams for medium and large rivers in the northern third of the world.
Regional	Anctil and Couture 1994	Examined effects of hydropower development on the fresh water balance of Hudson Bay
	Benke 1990	Quantified fragmentation of rivers in the continental USA by dams.
River	Ward and Stanford 1983	Introduced the Serial Discontinuity Concept stating that multiple dams along a river resulted in discontinuities in ecological parameters.
	Dynesius and Nilsson 1994	Presented the Fragmentation Index that assigned a fragmentation score to rivers based on the distance of the longest fragment divided by the total distance of the river.

Table 3.2. Hydropower plants in operation in the Sarapiqui River watershed.
Source: ICE, Dept. de Generacion Privada; ICE, Dept. de Proyectos Hidroeléctricos.

Name	River	General location	Installed capacity(MW)	Began operation	Ownership
El Angel	Rio Angel Rio Sarapiqui	Cinchona	3.9	1991	Private
Suerkata	Rio Sarapiqui	Vara Blanca	2.7	1995	Private
Don Pedro	Rio San Fernando	San Miguel	14.0	1996	Private
Volcan	Rio Volcan Rio Volcancito	San Miguel	17.0	1997	Private
Dona Julia	Rio Puerto Viejo Q. Quebradon	Cubujuqui	18.0	1999	Private
Rio Segundo	Rio Segundo	Bajos del Toro	0.7	1998	Private
Toro I	Rio Toro	Bajos del Toro	23.2	1995	Public (ICE)
Toro II	Rio Toro Quebrada Gata Rio Poza Azul Rio Claro	Bajos del Toro	65.9	1996	Public (ICE)

Table 3.3. River kilometers dewatered as a result of hydropower project operations.

Hydropower project	**River**	**Km dewatered**
Dona Julia	Puerto Viejo	4.12
Dona Julia	Quebradon	2.31
Angel	Angel	8.49
Toro	Toro	5.24
Toro	Gata	1.55
Don Pedro	San Fernando	6.44
Volcan	Volcan	7.37
Suerkata	Sarapiqui	1.07
Rio Segundo	Segundo	1.93
TOTAL (% total streams)		**30.9 (0.9)**

Table 3.4. Kilometers of river and forest cover upstream from dams in the Sarapiquí watershed. Percent total refers to the percentage of total length of that order of streams in the entire Sarapiqui watershed.

Hydropower project	**Sub-Basin**	**Total river km upstream**	**Upstream river km (% total)**			**Forest cover (ha) in sub-basin**	**% Forested area in sub-basin**
			1st order	**2nd order**	**3rd order**		
Dona Julia	Puerto Viejo River	73.2	45.9 (2.5)	12.4 (1.9)	12.9 (3.1)	5845.8	100.0
Dona Julia	Quebradon stream	7.2	7.2 (0.4)	0	0	908.6	100.0
El Angel	Angel River	36.4	23.9 (1.3)	12.0 (1.9)	0.5 (0.1)	2025.6	93.0
Toro	Toro River	72.2	48.4 (2.6)	17.2 (2.7)	6.6 (1.6)	4379.7	59.3
Toro	Gata Stream	15.3	14.3 (7.7)	1.1 (0.2)	0		
Don Pedro	San Fernando River	37.7	22.4 (1.2)	9.5 (1.5)	5.8 (1.4)	1909.4	93.7
Volcan	Volcan River	38.5	28.2 (1.5)	9.0 (1.4)	1.3 (0.3)	1956.0	92.3
Suerkata	Sarapiqui River	26.3	18.0 (1.0)	5.8 (1.0)	2.5 (0.6)	929.5	60.6
Rio Segundo	Segundo River	8.5	7.2 (0.4)	1.3 (0.2)	0	922.7	87.7
TOTAL		**306.8 (9.4)**	**208.3 (11.2)**	**67.0 (10.4)**	**29.6 (7.2)**	**18877.3**	**85.3 (average)**

**The Segundo River basin is a subwatershed of the Toro River. Thus, the total river km upstream from this dam are not included in the total since they were already accounted for in the river km upstream from the Toro project on the Toro River.

Table 3.5. Projected impacts of Cariblanco Hydropower Project on connectivity in the Sarapiquí River watershed. Percent total refers to the percentage of total km of that order of streams in the entire Sarapiqui watershed.

River	Km dewatered	Total river km upstream	Upstream river km 1st order	2nd order	3rd order	4th order	% forest cover
Sarapiqui River	9.33	108.4	68.4	22.8	12.9	4.3	73.2
Maria Aguilar River	3.17	9.1	8.7	0.4	0	0	59.4
Cariblanco River	2.06	27.0	24.2	2.4	0.4	0	90.7
Quicuyal River	1.56	17.9	12.5	5.5	0	0	86.5
TOTAL (% total)	**16.12**	**162.4 (5.0)**	**106.8 (5.7)**	**31.1 (4.8)**	**13.3 (3.2)**	**4.3 (2.1)**	**77.45 (ave.)**

** Totals for kilometers upstream overlap with calculations for kilometers upstream from the existing Suerkata Hydropower Project, also located on the Sarapiqui River. By subtracting these overlapping kilometers, the projected impacts of Cariblanco are 136.1 total river kilometers upstream; 88.8 km of 1st order streams; 25.3 km of 2nd order streams; 10.3 km of 3rd order streams. Kilometers dewatered and % forest cover are unaffected by these new calculations.

Table 3.6. Conversion of forest to other land uses in Sarapiqui County between 1976 and 1996. Adapted from Sanchez-Azofeifa et al. 1999.

Parameter	**1976**	**1986**	**1991**	**1996**
Forested area (km^2)	513	381	345	313
% of landscape	55	41	37	34

Table 3.7. Legal vs. illegal fishing methods in the Sarapiquí watershed.
(Based on information provided by E. Paniagua, park guard, La Selva Biological Station)

Legal fishing	**Abuses**	**Environmental consequences**
Time: 5 am – 5 pm	Night fishing with lights	Difficult for park guards to monitor fishing techniques and number of individuals captured.
Season: All year except for the months of Sept-Nov for fish and May for shrimp	Fishing during restricted months	Fishing during reproduction could affect future populations through reduced reproduction.
Size: Fish must be >25 cm	Fishing smaller individuals (abuses rare)	Fishing for immature animals could affect future populations by decreasing survivorship to age at maturity.
Number: 5 individual fish and 10 shrimps per person per day.	Collection of many more than the legal number of individuals	Overfishing results in population declines of target species.
Method: Hook and line	Use of spear guns (arbaleta); cast nets (atarraya); seine nets (trasmayo); harpoons (harpón); agricultural chemicals or pesticides (veneno); machetes (machetear); dynamite (bombas)	Illegal methods make fishing much easier and substantially increase the number of individuals per unit effort. Also, the use of chemicals negatively affects water quality and other aquatic organisms.
License: Obtained from the Minister of the Envt. (MINAE)	Fishing without a license (estimated 90% of fishermen in Sarapiqui)	Hinders watershed management and protection due to lack of documentation and lack of funding of management agencies.

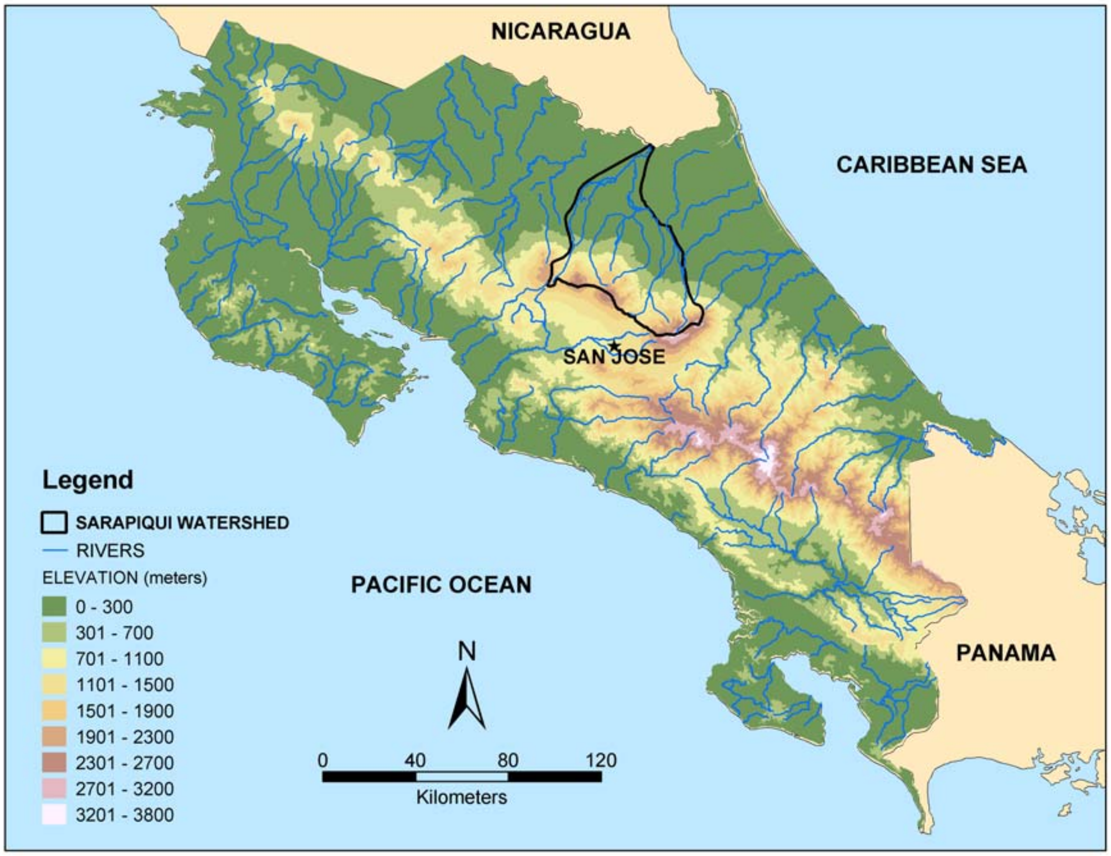


Figure 3.1. The Sarapiquí river system drains part of the northern Caribbean slope of Costa Rica and encompasses an altitudinal gradient of ~3000 m to near sea level. It is one of 34 major watersheds in the country. (Figure by Antonio Trabucco)

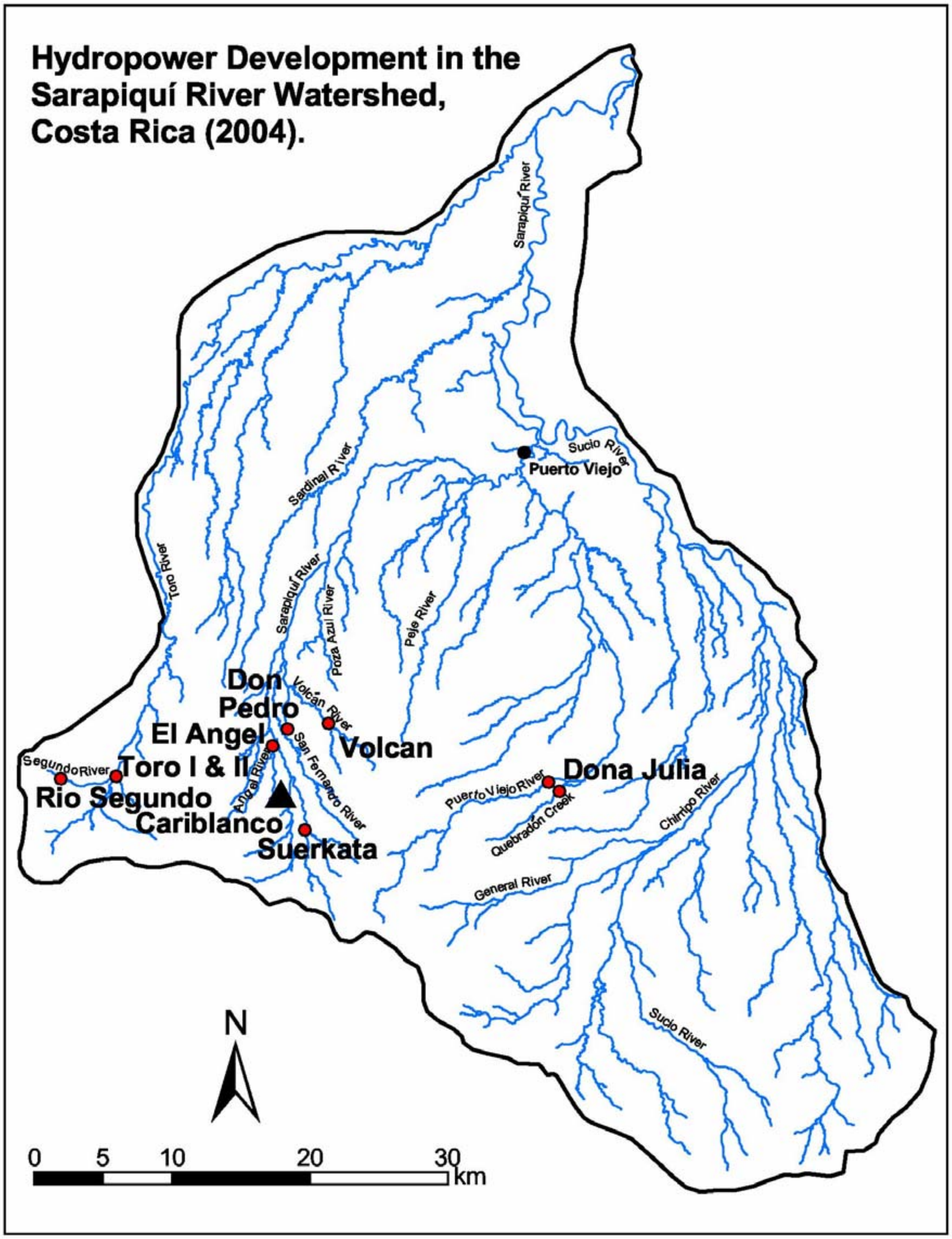


Figure 3.2. Hydropower development in Sarapiquí is concentrated in the upper watershed where there are abrupt changes in elevation. The locations of eight existing hydropower projects are indicated by a red circle on the map. The site for the proposed Cariblanco hydropower project is indicated with a black triangle. Also, the old gauge on the Sarapiquí River is just downstream from the town of Puerto Viejo, before the confluence of the Sucio River. (Figure by M. Snyder).

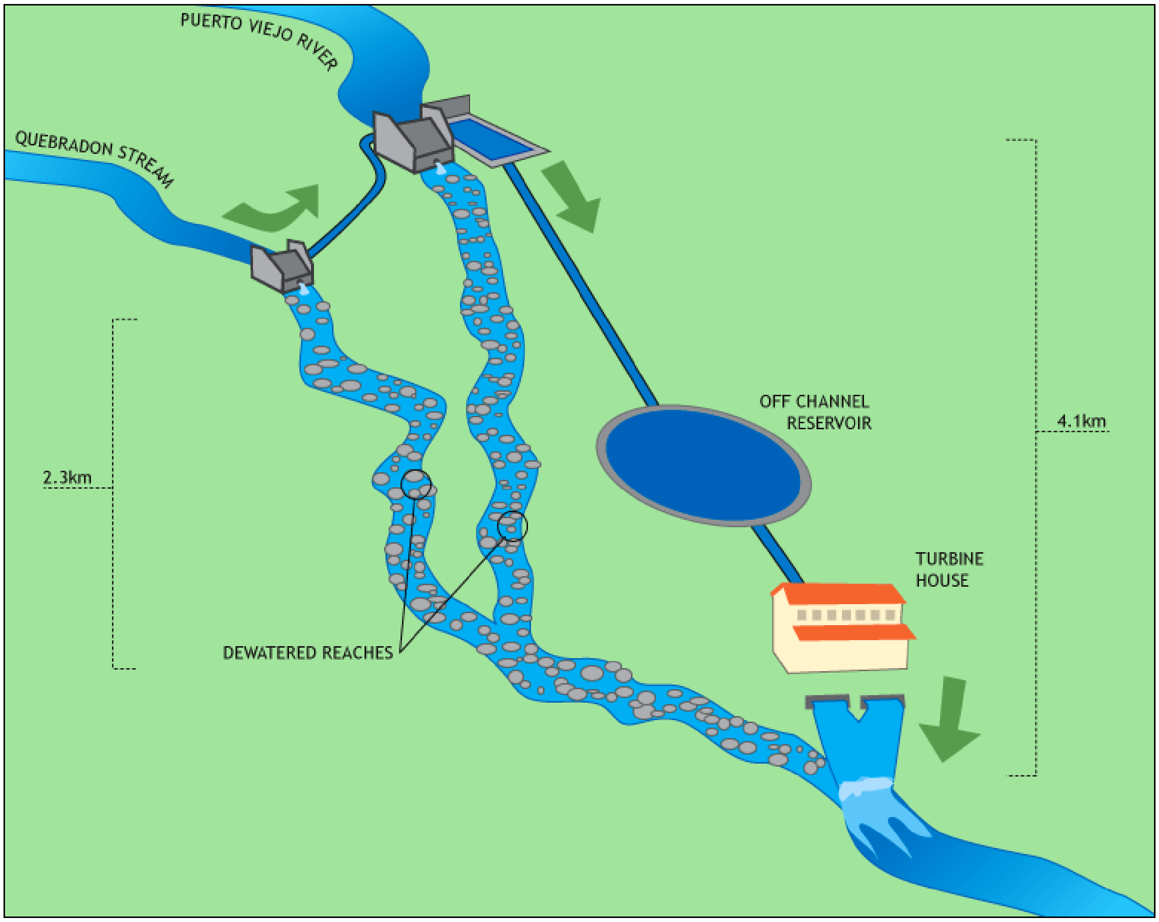


Figure 3.3. Schematic showing the operations of most hydropower projects in Sarapiquí. The dam(s) blocks flow and diverts water into a tunnel or pipeline to a reservoir. Water is run down a gradient to turbines and used to generate electricity and then returned to the river. This figure is based on the Doña Julia Hydroelectric Center, which operates with dams on two rivers. (Figure courtesy of Chesley Lowe).

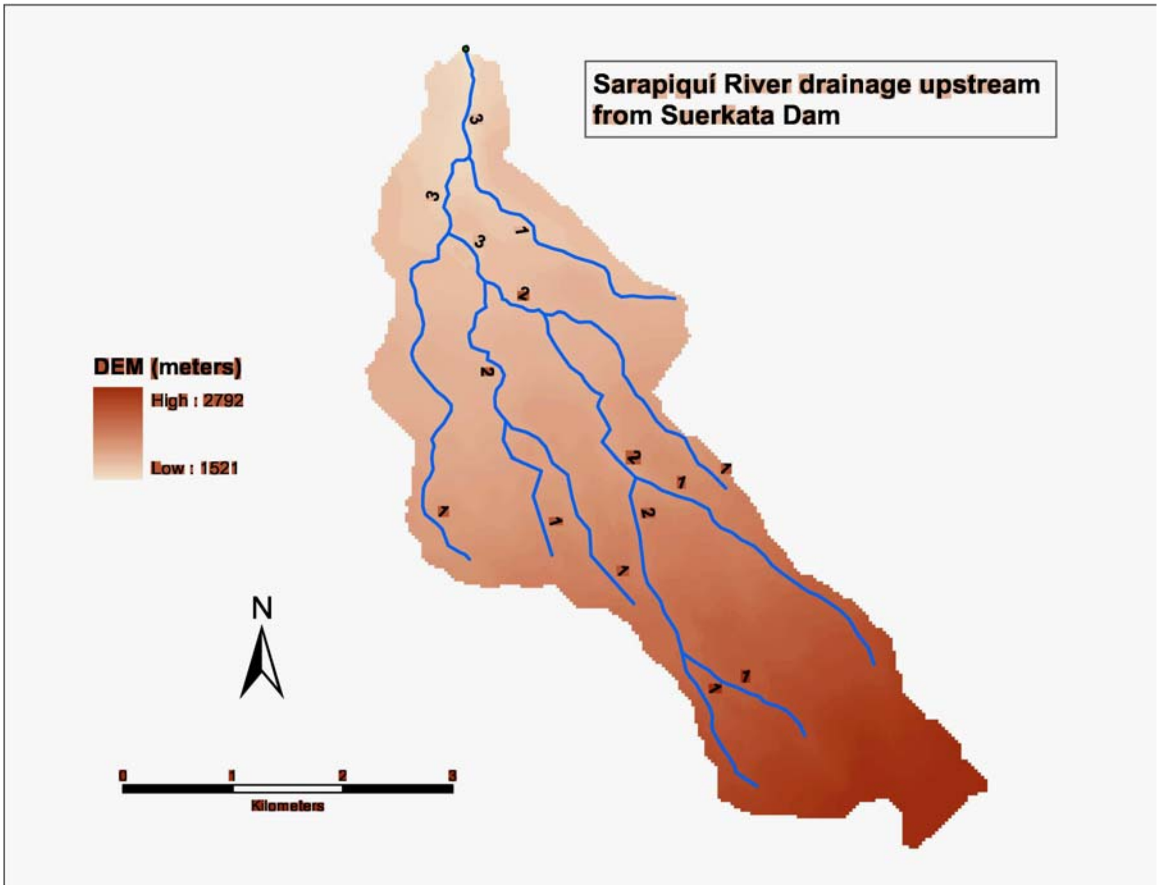
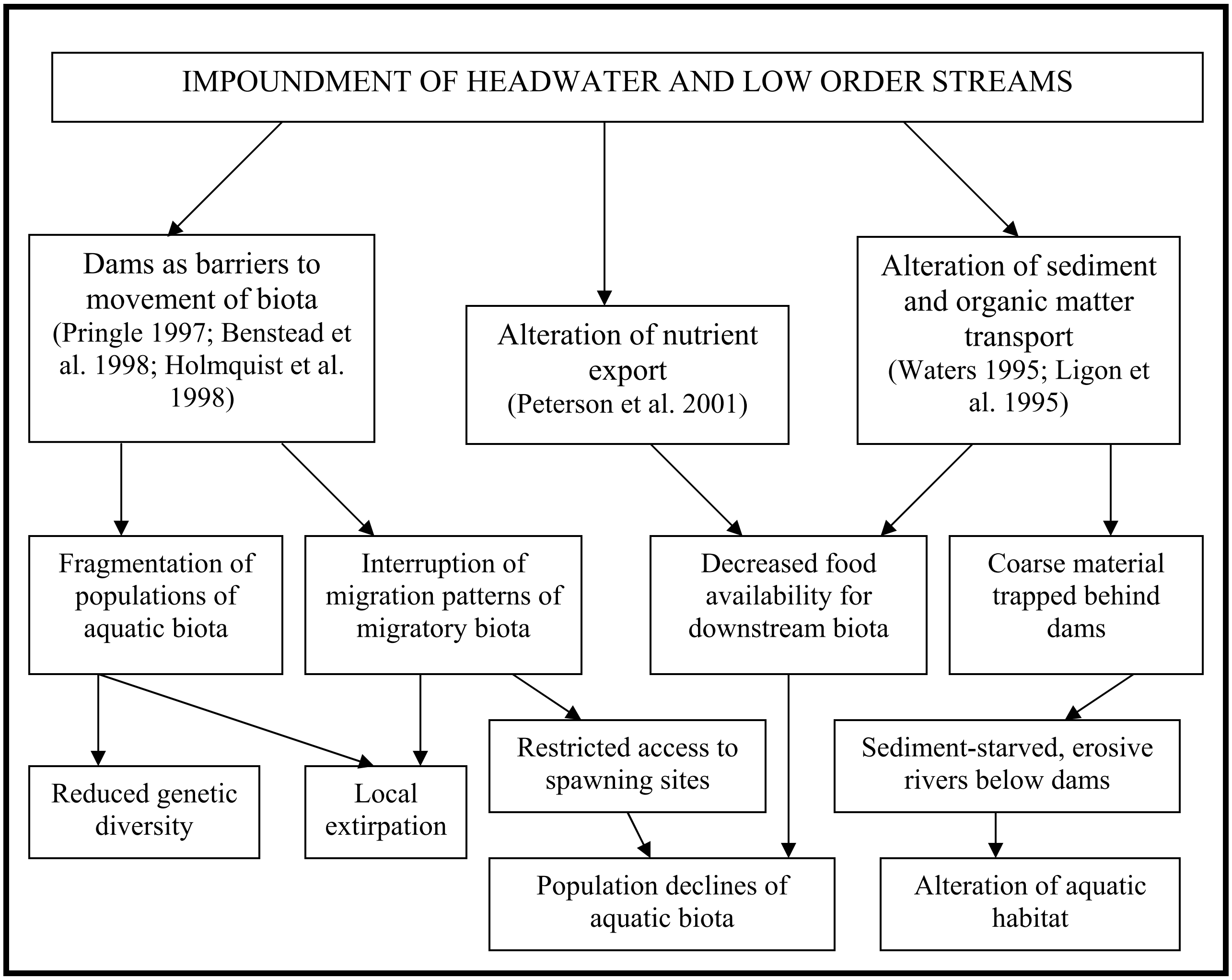


Figure 3.4. Strahler ordination of streams upstream from the Suerkata hydropower project on the Sarapiquí River. (Figure courtesy of Antonio Trabucco)

Figure 3.5. Ecological consequences of concentrated hydropower developments on headwater and low-order streams.



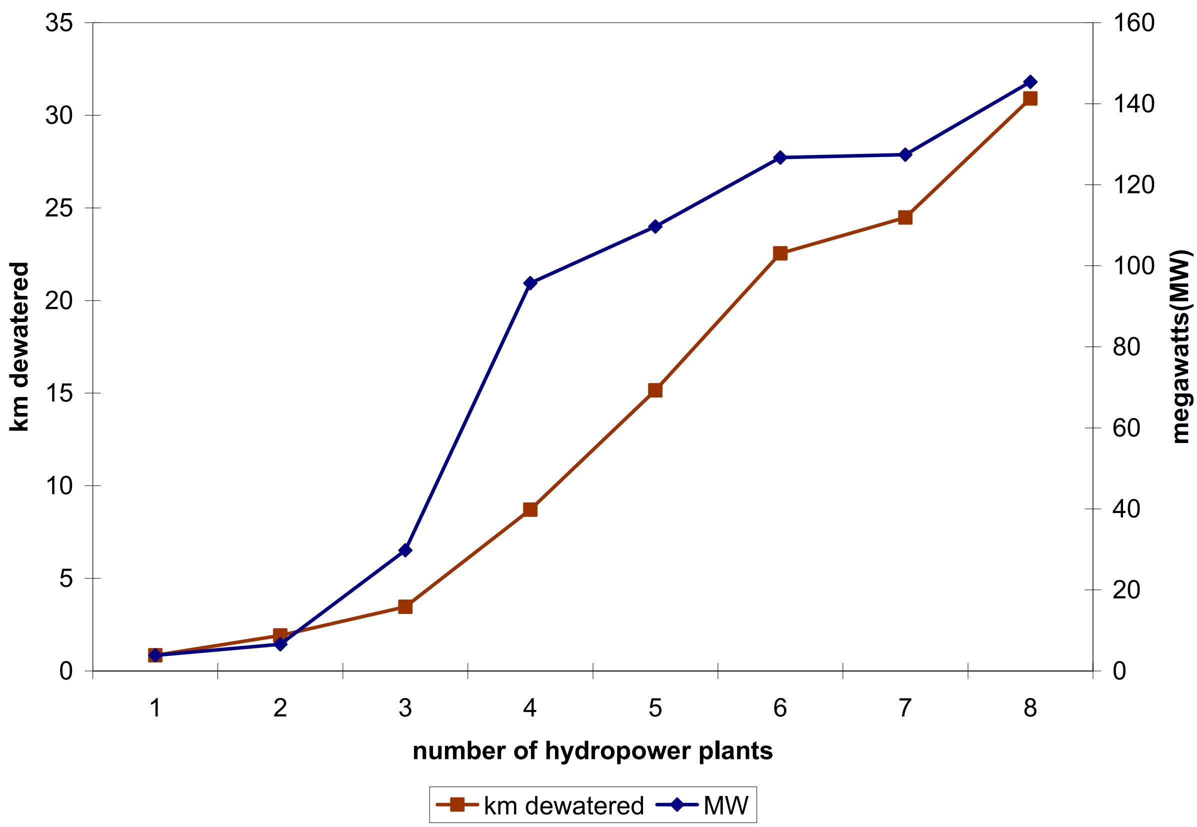


Figure 3.6. The total number of stream km dewatered increased with the construction of each additional hydropower plant. However, the number of km dewatered doesn't correspond uniformly to the number of megawatts of electricity produced.

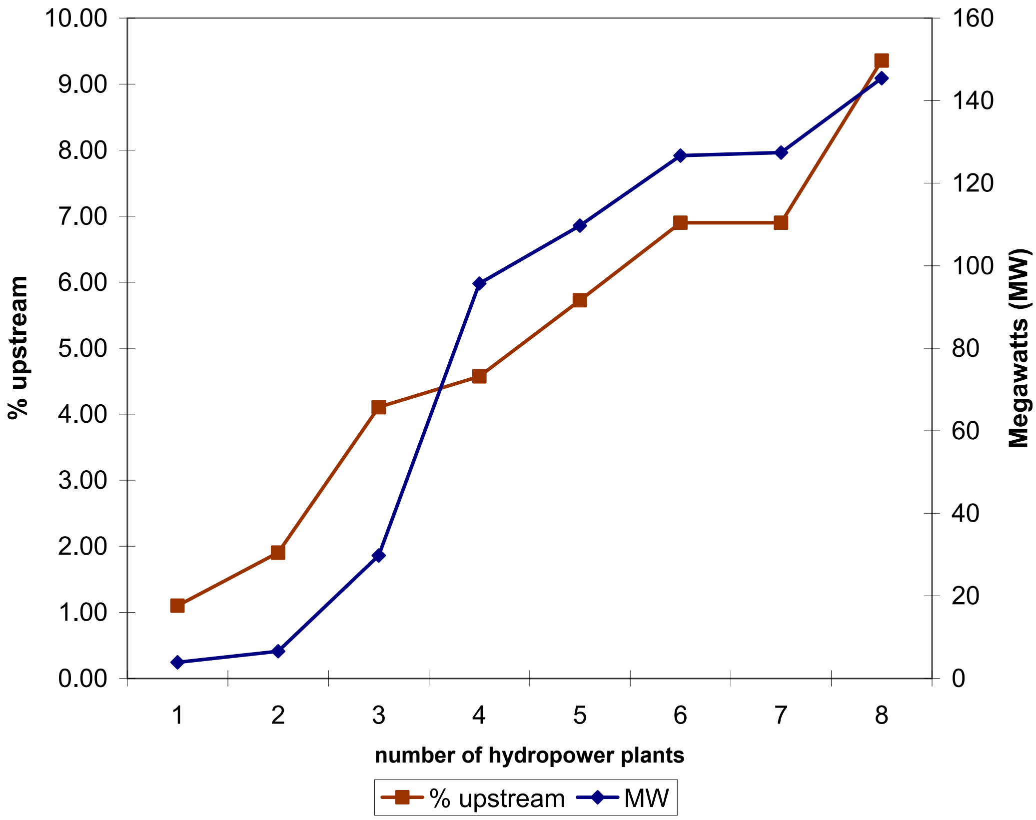


Figure 3.7. The percentage of stream length in the watershed that is upstream from dams increased with the construction of each additional hydropower project.

CHAPTER 4:

IMPACTS OF A WATER DIVERSION DAM ON NEOTROPICAL FISH ASSEMBLAGES, COSTA RICA[1]

[1]Olivas, E.A., Freeman, M.C., and Pringle, C.P. To be submitted to River Research and Applications

Abstract

Diversion dams for hydropower are becoming a pervasive feature in the landscapes of tropical regions. While most countries require some sort of environmental impact assessment prior to the construction of a dam, follow-up studies of ecological impacts of dam operation are rare. In this chapter, we present the results of a study of the ecological impacts of a small hydropower project on the upper Puerto Viejo River, Costa Rica. Specifically, we examined the impacts of project operations and the presence of two water diversion dams on stream fish assemblages and aquatic habitat. By investigating changes in fish assemblages with respect to downstream distance from a diversion dam along a de-watered reach of the Puerto Viejo River. Our results suggest that there is a measurable effect of dam operations and stream dewatering on fish assemblages. The fish assemblage at the upstream end of the de-watered reach of a 3rd order river resembled the assemblage of a 1st order stream. Our data also indicated a general but non-significant trend towards increasing species richness with downstream distance from the diversion dam. In addition, fishes with opportunistic life history strategies dominated assemblages closest to a water diversion dam, whereas cichlids (equilibrium-type life history strategists) were restricted to the latter half of the 4.4 km de-watered reach of the Puerto Viejo River. This study was conducted one year after the project's construction and our dataset serves as a foundation for monitoring changes in fish assemblages in the upper Puerto Viejo River.

Keywords: small dams, tropical, Costa Rica, streams, fish, hydropower

Introduction

The rapid conversion of pristine, free-flowing tropical rivers into regulated systems is currently one of the most pressing concerns in global freshwater conservation (Allan and Flecker 1993; Fearnside 1995; Dudgeon 2000; Pringle et al. 2000a,b). Expanding human populations and subsequent increases in demands for water and power have resulted in the construction of hundreds of dams on tropical rivers over the last two decades (Petts 1990; Vaux and Goldman 1990; WCD 2000). Large dam projects in the tropics have traditionally attracted attention from the international conservation community, due to their widespread environmental and social impacts (Goodland et al. 1993; Fearnside 1995; Rosenberg et al. 1995; Rosenberg et al. 1997). However, much of the dam development currently occurring throughout the tropics involves small or medium sized projects (Vaux and Goldman 1990; Majot 1997; Benstead et al. 1999; March et al. 2003). Unfortunately, the ecological impacts of these developments are poorly understood and are not being adequately documented.

The use of Environmental Impact Assessment (EIA) prior to dam development has become common in most countries and has aided in identifying projects that are excessively detrimental to river systems (Bonnell and Storey 2000). Despite its conservation benefits, in tropical regions, environmental impact assessment is challenged by a general lack of scientific data on tropical rivers and their biota (Winemiller 1996). While many EIAs provide only a cursory review of an area based on a few days' fieldwork, they often represent the first or only documentation of biotic assemblages in some tropical rivers. As a result, the potential impacts of dams in the tropics are frequently predicted or derived from studies of large dams on temperate rivers (Pringle et al. 2000a). Several fundamental differences between tropical and temperate rivers, such as seasonality, frequency and magnitude of floods, temperature regime, and faunal life histories, imply that this approach is inappropriate and manifest the need for more scientific research on tropical aquatic systems (Pringle 2000). Furthermore, every pre-dam EIA should be accompanied by follow-up studies of ecological impacts after dam operation begins to increase our understanding of how stream ecosystems respond to specific dam-induced changes. Unfortunately, these follow up studies are seldom completed (Travnichek et al. 1995).

Costa Rica has experienced a proliferation of small dams (<15 m high) on several of its watersheds during the last 15 years (Anderson 2002). As in much of Latin America, a large percentage (~85%) of Costa Rica's electricity is now generated by hydropower, but most of the country's hydroelectric potential still remains untapped (Anderson 2002). Studies of the environmental impacts of dams on Costa Rican rivers may provide insights into the relationship between future developments and freshwater resources in many tropical areas. By law, virtually all dam projects in Costa Rica are required to complete an EIA during their planning phase; these reports must be reviewed and approved by the minister of the environment (MINAE) before dam construction can begin. However, scientific studies of the actual ecological impacts of dam operations are rare or non-existent in Costa Rica.

In the mid-1990s, the Doña Julia Hydroelectric Company began construction of a hydropower project on the Puerto Viejo River, Costa Rica. The project is located in a remote area of Costa Rica, which was inaccessible by road until it was slated for hydropower development. Before project construction began, the company completed an EIA that included rudimentary information on the biotic and abiotic characteristics of the Puerto Viejo River, collected during April and May 1992 (Flores and Soto 1992). Based on this information and observations made during visits to the site during the construction and early operation phases, we predicted two major impacts of the Doña Julia project on the river: (1) the disruption of longitudinal riverine connectivity created by two concrete dams on the Puerto Viejo and a tributary stream; and (2) the de-watering of several stream kilometers and subsequent alteration of aquatic habitat. We hypothesized that the project's operation would affect the composition of fish assemblages in the Puerto Viejo River both upstream and downstream of the dam.

This study examined effects of the Doña Julia hydropower project's two small (<10 m high) dams and associated water diversion on the distribution and abundance of tropical stream fishes in the upper Puerto Viejo River. To the best of our knowledge, the present study is among the first in Costa Rica to investigate the ecological impacts of a diversion dam during its operational phase. We began data collection ~1 yr after the project started full operation. Our main objectives were to describe aquatic habitat and fish assemblages near the Doña Julia project on the Puerto Viejo River, Costa Rica, and to investigate potential patterns of fish species distribution along a de-watered reach of stream below the dam. The specific questions addressed were:

(1) Is it possible to measure an effect of the hydropower project's operations on fish assemblages? If so, is that effect related to aquatic habitat conditions?
(2) Is there a detectable change in fish assemblages and aquatic habitat with increasing distance from the diversion dam along a de-watered reach of river?

Study site: The Puerto Viejo River and the Doña Julia hydropower project

The Puerto Viejo River, located on the northern Caribbean slope of Costa Rica, drains part of Braulio Carrillo National Park, one of the largest tracts of protected rain forest in Central America that spans elevations from near sea level to 2,900 meters above sea level. Natural forest is the dominant land cover near the headwaters and mid-reaches of the Puerto Viejo drainage;

pasture and croplands are the major land uses in the river's lower watershed. Steep gradients caused by elevational changes of >100 m/km characterize the upper Puerto Viejo River watershed, which receives >4 m of precipitation annually. The watershed experiences wet (May to Dec) and dry (Jan to April) seasons, although precipitation is more evenly distributed throughout the year than in other parts of Costa Rica (Sanford et al. 1994).

Variable topography and year-round rainy conditions have created a large hydropower potential for the upper watershed of the Puerto Viejo River. Since 1999, the Doña Julia Hydroelectric Company has operated an 18-megawatt hydropower project on the river near the border of the national park (Figs. 4.1 & 4.2). The project draws water from the Puerto Viejo River and the Quebradon stream; these rivers carry respective mean annual discharges of 8.5 m^3/s and 1 m^3/s at the dam site, respectively (CLC Ingenieros 1994). The project's main function is to provide electricity to Costa Rican residents during peak hours of demand, which occur between approximately 10:00-12:30 and 17:30-20:00 daily. In 1999, the project produced enough electricity to satisfy 1.4% of the country's consumer needs (R. Corrales, personal communication).

Operation of the project has created a 'de-watered' reach of stream on both rivers, where 90-95% of the average annual discharge is removed from the river and piped to an off-channel reservoir for storage until electricity generation (Figure 4.3). On the Puerto Viejo River and Quebradon stream, the distance of the 'de-watered' reach corresponds to ~4 km and ~1 km, respectively. During normal flow conditions, a constant compensation discharge, calculated as approximately 5% of average annual flow, is left in the stream at each diversion site. On the Puerto Viejo River, tributary inputs (e.g., from Quebradon stream and other smaller 1st order streams) and groundwater seeps (E. Olivas, personal observation) incrementally increase the compensation discharge such that flow at the downstream end of the dewatered reach is roughly 10% of average annual discharge. During flood events or flows that surpass the capacity of the diversion canal (~16 m^3/s), the 'de-watered' reach fills with the excess water that passes over the dam. Based on long-term discharge records, flows >16 m^3/s occur 34 days per year on average (CLC Ingenieros 1994). Most of these days usually are concentrated during months of heaviest rainfall, such as November, December, and July.

Operation of the dam has also created variable conditions in the reach downstream from the turbines where water is returned to the river. Generation periods result in marked increases in discharge over several kilometers, due to the large amount of water released from the turbines during a short time period (Figure 4.4a). Discharge increases are accompanied by temperature decreases (Figure 4.4b).

Fish assemblages of the Puerto Viejo

A total of 44 freshwater fish species have been recorded from the Puerto Viejo River in the lowlands (Bussing 1993; E. Olivas, unpublished data). Most of these fishes were collected in 1962-63 during a comprehensive study of a 1 km reach near the mouth of the river in the vicinity of La Selva Biological Station (Bussing 1993). Collections of fishes in the Puerto Viejo River after the 1960s have been very limited (Burcham 1988; Coleman 1999), and the watershed has since experienced a dramatic conversion of much forested land to pasture and other agricultural land uses (Butterfield 1994; Vargas 1995; Reid 1999).

Methods

This study was conducted during January 2001-June 2002. To test for an effect of dam operations on fish assemblage composition, we sampled fish once during the ‘dry’ season (Feb-April 2001) and once during the ‘wet’ season (July-November 2001) at four sites on the Puerto Viejo River and two sites on the Quebradon stream. Sampling sites were selected based on their accessibility and location relative to the dam’s water diversion sites and turbine house. These sites consisted of stream reaches that were 20 times the mean width of the channel, or a maximum length of 300 m (Figure 4.1). To test for a pattern in fish assemblage composition along the de-watered reach, we sampled fish during the dry season (Jan-April 2002) at eight study sites located along the Puerto Viejo River between the water diversion and water return (Figure 4.1). Sampling sites consisted of 100 m long reaches and were selected using a stratified random study design based on downstream distance from the dam. To supplement the study, pools >1 m deep along the de-watered reach (13 total) also were sampled for fishes.

Fish sampling

We used a Smith-Root backpack electrofisher for all fish collections. In 2001, all fishes captured during one pass of each study reach were measured for standard length, identified to species, and then returned to the river. A voucher collection was deposited at the Museum of Natural History at the Universidad de Costa Rica in San José, Costa Rica. In 2002, we used the removal method (White et al. 1982) to examine fish assemblages along the de-watered reach. Block nets were placed at the upstream and downstream ends of each 100 m study reach and three passes of the reach were made with the electrofisher, moving in an upstream direction. After completing a pass, fish were identified to species and measured for standard length. Fish were released ~100 m from the block net at the downstream end of the reach to prevent recapture in subsequent passes.

Visual assessments were conducted in pools >1 m deep and consisted of timed trials performed by two observers. Using a mask and snorkel, observers took turns slowly swimming a pre-determined route through the pool during a 10 min period, noting all fish species present in the pool. These 10 min trials were repeated three times by each observer, for a total sampling time of 60 min in each pool. In two pools where no fish were seen during the first three trials, the sampling period was stopped after 30 min. In cases where an observer was uncertain about species identification, both observers returned to the pool after the 60 min period to note specific characteristics about the fish and its behavior. Based on this information, fish were identified to species using Bussing (1998). Pool volume and visibility were estimated after the observation period to assist with comparisons.

Habitat descriptions

Physical variables related to aquatic habitat were measured at all sites in 2001 and 2002. These included temperature, water velocity, substrate, wetted channel width, and water depth. In 2001, Onset Stowaway Temperature Dataloggers recorded temperature at two sites on the Quebradon stream (QQA; QQD), three sites on the Puerto Viejo River (PVA; PVDM; PVCQ), and at the water release from the turbine house (PVCU) during Feb-April. Geomorphic channel units were mapped using 50 m measuring tapes to estimate the percentage of pools and rapids at each site and to measure channel width. Using a stratified random study design, we sampled water velocity, depth, and dominant substrate at 1 m intervals along 10 bank-to-bank channel cross-sections (5 in pools and 5 in rapids) at each of the six sites. We also collected two water samples from each of the six study sites that were later analyzed for soluble reactive phosphorus, nitrate, and ammonium at the UGA Institute of Ecology's Analytical Laboratory.

In 2002, Onset Stowaway Temperature Dataloggers were placed at three points to record differences in single maximum and minimum temperatures along the de-watered reach of the Puerto Viejo River: 100 m downstream from the diversion dam, 2000 m from the dam, and 4200 m from the dam. Water velocity (using a Marsh-McBirney FloMate meter) and depth were sampled at 1 m intervals along 10 channel cross-sections, spaced equidistantly along each 100 m study reach. A pebble count (Wolman 1954) was used to identify dominant bed sediment, and geomorphic channel units were mapped in each of the eight 100 m study reaches after fish and other habitat sampling was completed.

Data analysis

To test for an effect of dam operations on fish assemblage composition (2001 sample data), we used non-metric multidimensional scaling (NMS) to ordinate a species abundance by sample (site and season) matrix of 2001 data. Our analysis was completed using PC-ORD software (MjM Software Design™, Glendale Beach, OR, U.S.A; McCune and Mefford 1999), using Sorenson similarity. Abundance data were root-root transformed (e.g., fourth root) prior to ordination. Species richness for each sample was estimated using the limiting form of the jackknife estimator described by Burnham and Overton (1979), and calculated using SPECRICH software provided by the Patuxent Wildlife Research Center (www.pwrc.usgs.gov). This estimator uses species count data to account for variability in capture probabilities among different species (see Burnham and Overton 1979). To test for longitudinal patterns in fish assemblage composition along the de-watered reach (2002 sample data), we estimated species richness from pooled data from all three passes at each 100 m study reach. This analysis was accomplished using the jacknife richness estimator. Species richness estimates from 100 m reaches and species count data from visual assessments in pools were tested against downstream distance from the dam using regression analysis. Regression analysis also was used to test for patterns in fish abundance (number of individuals) with downstream distance from the dam.

Results

Fishes: Distribution and abundance near hydropower project

A total of 2401 individuals were collected by electrofishing from the Puerto Viejo River and Quebradon stream, 1519 individuals in 2001, and 882 individuals from the de-watered reach of the Puerto Viejo in 2002. Captured fishes represented 14 species in 6 families (Table 4.1). In 2001, the most common species captured was *Poecilia gillii* (Poecilidae), which accounted for 43.5% of all individuals. *Rhamdia rogersi* (Pimelodidae), which accounted for 23.5% of individuals, was the second most common species in 2001. *Poecilia gillii* was also the dominant species captured in 2002, accounting for 46.0% of all individuals captured along the de-watered reach. Despite few individuals (only 22 captured in total), the most species-rich family was Cichlidae, with 5 species. No additional species were recorded during visual assessments.

Ordination of 2001 data indicated that samples (site and season) were divided into three distinct groups based on fish assemblage composition (Figure 4.5). The largest group included all four samples from the Quebradon stream (QQAD; QQAW; QQDD; QQDW) and both samples from the Puerto Viejo River directly below the dam (PVDD; PVDW). Samples taken from the Puerto Viejo River at the end of the de-watered reach (PVCQD; PVCQW) clustered with samples taken downstream from the water return (PVCUD; PVCUW) to form the second group. Dry and wet season samples taken above the dam on the Puerto Viejo River (PVAD; PVAW) formed the third group. Together, axes 1 and 2 represented 91% of the variation in the original distance matrix. The ordination also indicated that fish assemblage composition was most affected by site location. Although slight seasonal differences in assemblages may exist, these differences were small in comparison with site differences. Separation of the groups was related to the occurrence of cichlids and increased abundance of individuals at the downstream sites (PVCQ; PVCU), and fewer individuals above the Puerto Viejo dam (PVA).

Estimated species richness varied by location and slightly by season at each location. Species richness was highest (11 spp.) downstream from the turbines (PVCUD) during the dry season and lowest (3 spp.) upstream from the dam on the Quebradon stream during the wet season (QAW). At sites within the dewatered reach of the Puerto Viejo River (PVDM; PVCQ), species richness was higher during the wet season, whereas at sites upstream from the dams (QA; PVA), species richness was higher during the dry season.

Fishes: Longitudinal patterns along the de-watered reach

Our data indicated that the removal method (White et al. 1982) was unsuccessful at estimating fish populations along the dewatered reach of the Puerto Viejo River. As required by the method, at all study reaches we captured the largest number of individuals during the first pass with the electrofisher and then substantially fewer individuals during the second pass. However, during the third pass, we typically captured many more individuals than the second pass and often as many as during the first pass. This result contradicted the requirement of the removal method that catches decline with additional passes. Therefore, we were never able to estimate population size with confidence from our data. In our study system, we believe that dominant bed sediments, such as boulder and cobble, may have created ample hiding spaces for fishes during the first and second passes, and then fish weakened by the electrofisher were caught during the third pass.

Analysis of 2002 fish data revealed some longitudinal patterns in species richness along the dewatered reach of the Puerto Viejo River (Table 4.2). Species count was highest at the downstream end of the dewatered reach (8 species) and linear regression of species richness estimates indicated a general but non-significant trend towards increasing fish species richness with downstream distance from the dam (r^2=0.25, p>0.05) (Figure 4.6). However, richness changed by only two species from the upstream to the downstream end of the dewatered reach. Overall fish abundance in samples at each study site was not significantly related to downstream distance from the diversion dam (r^2=0.14, p>0.05). Peaks in the number of individuals captured occurred at 1484 m and 4179 m downstream from the dam; these peaks resulted from the dominance of *Poecilia gillii*, which accounted for more than half of the individuals at each of these two sites (Figure 4.7).

Data from visual assessments along the de-watered reach of the Puerto Viejo River revealed that fish species counts in pools were significantly related to downstream distance from the dam (r^2=0.73, p<0.01) (Figure 4.8). Cichlid fishes, found only in pools in the latter half of the de-watered reach (>2500 m downstream from the diversion dam), accounted for this increase in species count.

Habitat descriptions

Basic habitat characteristics of all sites are shown in Table 4.3. Several trends are evident in the data. Rapids and riffle habitats tended to compose a larger percentage of the channel at sites upstream from the dam than at downstream sites within the dewatered reach, where pool or low velocity habitats dominated. Water velocity in both pools and riffles was 4-10 times greater at sites upstream from the dams than in de-watered reaches. Water depths tended to be greater at upstream sites as well, with the exception of greater average riffle depth at one site within the dewatered reach (Table 4.3). However, there were no significant relations between distance downstream from the dam and average depth or velocity in pools (r^2=0.1; r^2=0.0004) or riffles (r^2=0.019; r^2=0.057), respectively. Boulder (250-4000 mm), followed by cobble (64-250 mm), was the dominant bed sediment at all sites. Minimum water temperatures tended to be lower at upstream sites, while maximum water temperatures were higher at downstream sites during Feb-April 2001 (Table 4.3a). Dewatering appeared to increase water temperature: during Feb-April 2001, single maximum water temperatures recorded from the Puerto Viejo River in the dewatered reach (PVDM) were ~2 ºC higher than temperatures upstream (PVA; Table 4.3a). Results were similar for the Quebradon stream; the single maximum temperature of the dewatered reach was ~1 ºC higher than upstream water temperature. Analysis of water samples for ammonium, nitrate, and phosphorus indicated that water chemistry of the Puerto Viejo River and Quebradon stream may be influenced by geochemical inputs from volcanic activity (see Pringle et al. 1993). Across all sites, average concentrations of nutrients were 7 µg L^{-1} (±3) of ammonium (NH_4-N), 70 µg L^{-1} (±21) of nitrate (NO_3-N), and 249 µg L^{-1} (± 94) of phosphorus (SRP).

Discussion

The Doña Julia Hydropower Project is representative of the ~30 private hydropower dams built in the past 15 years in Costa Rica (Anderson 2002). While the potential environmental impacts of such developments are often predicted before their construction, the actual ecological impacts of dam operations are usually not documented. Our investigation of the ecological impacts of hydropower project operation is one of the only studies of its kind in Costa Rica.

Fish assemblages of the upper Puerto Viejo River

The present study marks the first comprehensive survey of the fishes of the upper Puerto Viejo River. An environmental impact statement completed as part of the planning process of Doña Julia Project claimed that multiple fish species inhabited the river in the area near the dam; these conclusions, however, were based on the existing literature and interviews with area residents. No field collections of fishes were reported in the environmental impact statement (Flores and Soto 1992). During the present study, we collected a total of 14 fish species from the upper Puerto Viejo River along a ~5 km reach. Of these, one species, *Agonostomus monticola*, is highly mobile and suspected to be either amphidromous or catadromous (Cruz 1987; Phillip 1993; Aiken 1998). An additional migratory fish, *Joturus pichardi*, was reported by local fishermen to have been abundant in the area in the past and mentioned in the environmental impact statement; yet this fish was not collected or seen during the present study.

Our results suggest that there is a measurable effect of dam operations on fish assemblage composition. This effect is most pronounced upstream and directly downstream from the dam on the Puerto Viejo River (PVA; PVDM). In the absence of the dam, we would expect these two assemblages to resemble one another, due to their close geographic proximity. However, our results indicate that the fish assemblage directly downstream from the dam (PVDM) is most closely related to assemblages of the Quebradon stream (QQA; QQD). The physical barrier presented by the dam restricts fish movement between the two sites on the Puerto Viejo (PVA; PVDM) and thus may influence the structure of the upstream assemblage. Whereas fish from upstream areas are capable of swimming downstream and passing over the dam during high flow conditions, the dam restricts upstream movement. A potential consequence of this restricted movement is the isolation of fish populations upstream from the dam. This isolation could result in decreased intraspecific genetic diversity or local extirpation of highly mobile species (Winston et al. 1991; Pringle 1997). Our data indicate that in the future *Agonostomus monticola* may face local extinction upstream of the dam: during the dry season we captured three large adults above the dam and observed four adults swimming at the base of the dam, yet during the wet season six months later we neither captured or observed any *Agonostomus monticola* upstream from the dam.

Similarity of certain aquatic habitat conditions may be the best explanation for the separation of the fish assemblages into three groups in the ordination analysis. The resemblance between the fish assemblage directly downstream from the dam on the Puerto Viejo (PVDM) and the assemblages of the Quebradon stream (QA; QD) may be explained by the fact that all three sites are comparable in terms of stream width, temperature range, and substrate. Additionally, average depth and velocity at the downstream site on the Puerto Viejo (PVDM) more closely resemble conditions in Quebradon stream than conditions upstream from the dam (Table 4.3). Lack of pool habitat and rapid water velocities, in addition to isolation caused by the dam, probably explain why the fish assemblage upstream from the dam on the Puerto Viejo River (PVA) was unlike any other. Warmer water temperatures, lower elevation, and increased stream width may be reasons for the similarity between assemblages at the downstream end of the dewatered reach (PVCQ) and below the water return (PVCU).

Longitudinal patterns to fish distribution along a de-watered reach

Our results indicate that there is a detectable change in fish assemblage composition downstream from the dam on the Puerto Viejo River. However, is this pattern actually the result of dam operations and if so, to what degree? Alternatively, do observed patterns reflect a natural longitudinal gradient of species additions, as has been predicted for Central American streams without large dams (Welcomme 1985)? The paucity of pre-impoundment data on natural fish distribution and the lack of comparable rivers in the region make it impossible to answer these questions with complete certainty. In addition, our inability to estimate capture efficiency and population sizes with removal sampling confounds interpretation of the results of this study. Nevertheless, some trends evident in our data can provide insights. For example, species count data from electrofishing and visual assessments in 2002 suggest that fish distribution may reflect a natural longitudinal pattern. Furthermore, classification of fish by feeding groups (e.g., insectivores, piscivores, omnivores, detritivores) and as either habitat generalists or specialists reveals no real trends in fish distribution along the dewatered reach. But when we classify fishes by their life history strategies (Winemiller 1995), our results indicate that species with more ‘opportunistic’ strategies dominate assemblages closer to the dam, whereas assemblages further downstream along the dewatered reach contain a mix of ‘opportunistic’ and ‘equilibrium’ species (Table 4.4). This distribution of ‘equilibrium’ species may be the result of incremental increases in discharge along the dewatered reach due to tributary and groundwater inputs, since they were only present downstream from the confluence of the Puerto Viejo River and the Quebradon stream. Increased discharge in the downstream half of the dewatered reach may mean three things for fishes: (1) more habitat during dry periods with little rainfall; (2) reduced disturbance during high or ‘flashy’ flows; and (3) easier access to refugia near channel edges. Furthermore, slightly lower minimum water temperatures at the upstream end of the dewatered reach may also explain why cichlids (equilibrium species) were restricted to downstream areas.

Conclusions and Recommendations

Perhaps the greatest value of our dataset is that it can be used as a tool for tracking changes over time in fish assemblages near the Dona Julia hydropower project. Changes could result from temporal adjustments to present operating conditions or in response to modifications in operation designed to minimize environmental impacts. Diversion dams, like the one on the Puerto Viejo River, hinder upstream movement of mobile / migratory fishes. Our results also imply that the increased likelihood of desiccation, downstream from a diversion dam before the confluence of any major tributaries, may be a mechanism limiting the occurrence of equilibrium-type species like cichlids. The presence of the dam and water diversion may impact long-term persistence of fish populations in the upper Puerto Viejo River.

If management goals at Doña Julia and other hydropower projects in Costa Rica include maintaining biotic integrity in dammed streams, alternatives to current operations should be considered. Providing fish passage at dams below 600 meters above sea level and increasing flows in diverted streams during dry periods may help facilitate upstream persistence of periodic- and equilibrium-type fish species. At higher altitudes, fish assemblages are dominated by only a few small species adapted to colder water temperatures (Bussing 1998). Because the Doña Julia dam and other private diversion dams in Costa Rica are usually <10 m in height, installation of a fish ladder or an artificial side channel may be practicable. Increasing flows in diverted streams could be accomplished in the context of adaptive management (Irwin and Freeman 2002): a trial period of augmented flows accompanied by fish sampling would show whether or not more periodic- and equilibrium-type species move upstream when discharge is increased. In absence of changes to current operations, we expect that fish assemblages in the upper Puerto Viejo

River, and other streams used for hydropower, will be increasingly dominated by opportunistic-type fishes.

In summary, dams like the Doña Julia hydropower project are currently transforming river ecosystems throughout the tropics. The ecological impacts of these developments on tropical rivers will depend on the type of facility, degree of hydrologic alteration, local climate, and life histories of stream biota. More studies of pre-impoundment ecological conditions are needed to provide insight into the ecological requirements of tropical stream biota and to predict their response to hydrologic alterations caused by dams. Establishment of monitoring programs and the use of adaptive management at operational dams can help guide future development in a way that maximizes the benefits of hydropower while minimizing its negative environmental consequences. This study and others (see Benstead et al. 1999; Ponton et al. 2000) illustrate the utility of ecological research in improving the design and management of dams and other water abstraction projects in the tropics.

Acknowledgements

This research was funded by a Fulbright scholarship (2001) to E. Olivas. Additional financial and logistical support was provided by the Organization for Tropical Studies. Indirect support came from a National Science Foundation grant (DEB-0075339) to C.M. Pringle and F.J. Triska. This study would not have been possible without the collaboration of the Doña Julia Hydroelectric Company, in particular Rafael Corrales, Antonio Sevilla, and Frank Daniels, who granted us unlimited access to the project site. We would like to thank the many people who assisted in the field, especially: Minor Hidalgo, Paulo Olivas, Enrique Salicetti, Jose Reñazco, William Ureña, Suzanne Moellendorf, and Heather Conwell. We also thank Antonio Trabucco and Chesley Lowe for preparation of figures 1 and 3 and Diana Lieberman for advice on data analysis. The Pringle Lab group, Judy Meyer, and Ronald Coleman provided insightful comments on earlier drafts of this manuscript.

Literature Cited

Aiken, K.A. 1998. Reproduction, diet and population structure of the mountain mullet, *Agonostomus monticola*, in Jamaica, West Indies. *Environmental Biology of Fishes* **53**:347-352.

Allan, J.D. and Flecker, A.S. 1993. Biodiversity conservation in running waters. *BioScience* **43**, 32-43.

Anderson (Olivas), E.P. 2002. Electricity sector reform means more dams for Costa Rica. *World Rivers Review* **17**(4):3.

Benstead, J.P., March, J.G., Pringle, C.M., and Scatena, F.N. 1999. Effects of a low-head dam and water abstraction on migratory tropical stream biota. *Ecological Applications* **9**, 656-668.

Bonnell, S. and Storey, K. 2000. Addressing cumulative effects through strategic environmental assessment: A case study of small hydro development in Newfoundland, Canada.

Burcham 1988. Fish communities and environmental characteristics of two lowland streams in Costa Rica. *Revista de Biologia Tropical* **36**, 273-285.

Burnham, K.P. and Overton, W.S. 1979. Robust estimation of population size when capture probabilities vary among animals. *Ecology* **60**, 927-936.

Bussing, W.A. 1993. Fish communities and environmental characteristics of a tropical rain forest river in Costa Rica. *Revista de Biologia Tropical* **41**, 791-809.

Bussing, W.A. 1998. *Peces de las Aguas Continentales de Costa Rica,* Editorial de la Universidad de Costa Rica, San Jose.

Butterfield, R.P. 1994. The regional context: Land colonization and conservation in Sarapiqui. Pages 299-306 in McDade, L.A., Bawa, K.S., Hespenheide, H.A., and Hartshorn, G.A. *La Selva: Ecology and Natural History of a Neotropical Rain Forest*.

CLC Ingenieros. 1994. Estudio de Factibilidad del Proyecto Hidroeléctrico Doña Julia. San Jose, Costa Rica.

Coleman, R. 1999. Cichlid fishes of the Puerto Viejo River, Costa Rica. *Cichlid News* **8**, 6-12.

Cruz, G. A. 1987. Reproductive biology and feeding habitat of Cuyamel, *Joturus pichardi* and Tepemechin, *Agonostomus monticola* (Pisces: Mugilidae) from Rio Platano, Mosquitia, Honduras. *Bulletin of Marine Science* **40**, 63-72.

Dudgeon, D. 2000. Large-scale hydrological alterations in tropical Asia: prospects for riverine biodiversity. *BioScience* **50**:793-806.

Fearnside, P.M. 1995. Hydroelectric dams in the Brazilian Amazon as sources of "greenhouse" gases. *Environmental Conservation* **22**, 7-19.

Flores, E.M. and Soto, R. 1992. Evaluación biologica del impacto ambiental del Proyecto Hidroeléctrico Doña Julia 18-V. San Jose, Costa Rica.

Goodland, R.J.A., Juras, A., and Pachauri, R. 1993. Can hydro-reservoirs in tropical moist forests be environmentally sustainable? *Environmental Conservation* **20**, 122-130.

Irwin, E.R. and Freeman, M.C. 2002. Proposal for adaptive management to conserve biotic integrity in a regulated segment of the Tallapoosa River, Alabama (U.S.A.). *Conservation Biology* **16**, 1-11.

Majot, J.A. (ed). 1997. *Beyond Big Dams: A New Approach to Energy Sector and Watershed Planning*. International Rivers Network, Berkeley, CA.

March, J.G., Benstead, J.P., Pringle, C.M., and Scatena, F.N. 2003. Damming tropical island streams: Problems, solutions, and alternatives. *BioScience* **53**, 1069-1078.

McCune, B. and Mefford, M.J. 1999. PC-ORD: Multivariate Analysis of Ecological Data, Version 4. MjM Software Design, Glenden Beach, OR.

Petts, G.E. 1990. Regulation of large rivers: Problems and possibilities for environmentally sound river development in South America. *Interciencia* **15**, 388-395.

Phillip, D.A.T. 1993. Reproduction and feeding of the mountain mullet, *Agonostomus monticola*, in Trinidad, West Indies. *Environmental Biology of Fishes* **37**:47-55.

Ponton, D., Merigoux, S., and Copp, G.H. 2000. Impact of a dam in the neotropics: what can be learned from young-of-the-year fish assemblages in tributaries of the River Sinnamary (French Guiana, South America). *Aquatic Conservation: Marine and Freshwater Ecosystems* **10**:25-51.

Pringle, C.M. 1997. Exploring how disturbance is transmitted upstream: going against the flow. *Journal of the North American Benthological Society* **16**:425-438.

Pringle, C.M. 2000. Riverine conservation in tropical versus temperate regions: Ecological and socioeconomic considerations. Pages 367-379 in Boon, P.J., Davies, B.R., Petts, G.E., eds. *Global Perspectives on River Conservation: Science, Policy and Practice*. John Wiley & Sons, New York.

Pringle, C.M., Freeman, M.C., and Freeman, B.J. 2000(a). Regional effects of hydrologic alterations on riverine macrobiota in the new world: tropical-temperate comparisons. *BioScience* **50**, 807-823.

Pringle, C.M., Rowe, G.L., Triska, F.J., Fernandez, J.F., and West, J. 1993. Landscape linkages between geothermal activity, solute composition, and ecological response in streams draining Costa Rica's Atlantic slope. *Limnology and Oceanography* **38**:753-774.

Pringle, C.M., Scatena, F.S., Paaby-Hansen, P., and Nunez, M. 2000(b). River conservation in Latin America and the Caribbean. Pages 39-73 in Boon, P.J., Davies, B.R., Petts, G.E., eds. *Global Perspectives on River Conservation: Science, Policy and Practice*. John Wiley & Sons, New York.

Read, J.M. 1999. *Land Cover Change Detection for the Tropics Using Remote Sensing and Geographic Information Systems*. PhD Dissertation, Louisiana State Univeristy. Baton Rouge, LA.

Rosenberg, D.M., Bodaly, R.A., and Usher, P.J. 1995. Environmental and social impacts of large-scale hydroelectric development: who is listening? *Global Environmental Change* **5**, 127-148.

Rosenberg, D.M., Berkes, F., Bodaly, R.A., Hecky, R.E., Kelly, C.A., and Rudd, J.W.M. 1997. Large-scale impacts of hydroelectric development. *Environmental Review* **5**, 27-54.

Sanford, R.L., Paaby, P., Luvall, J.C., and Phillips, E. 1994. Climate, Geomorphology, and Aquatic Systems. Pages 19-33 in McDade, L.A., Bawa, K.S., Hespenheide, H.A., and Hartshorn, G.A. *La Selva: Ecology and Natural History of a Neotropical Rain Forest*. University of Chicago Press, Chicago.

Travnichek, V. H., Bain, M. B., and Maceina, M. J. 1995. Recovery of a warmwater fish assemblage after the initiation of a minimum-flow release downstream from a hydroelectric dam. *Transactions of the American Fisheries Society* **124,** 836-844**.**

Vargas, R.J. 1995. *History of Municipal Water Resources in Puerto Viejo de Sarapiquí, Costa Rica: A Socio-Political Perspective*. Master's thesis, University of Georgia. Athens, GA.

Vaux, P.D. and Goldman, C.R. 1990. Dams and development in the tropics. Pages 101-123 in Goodland, R. editor. *Race to Save the Tropics*. Island Press, Washington, DC.

Welcomme, R.L. 1985. River fisheries. FAO Fisheries Technical Paper **262**, 1-330.

White, G.C., Anderson, D.R., Burnham, K.P., and Otis, D.L. 1982. *Capture-Recapture and Removal Methods for Sampling Closed Populations*. Los Alamos National Laboratory, Los Alamos, NM.

Winemiller, K.O. 1995. Aspects structurels et fonctionnels de la biodiversite des peuplements de poissons. *Bulletin Francais du Peche et Pisciculture* **339**, 23-45.

Winemiller, K.O. 1996. Dynamic diversity in fish assemblages of tropical rivers. Pages 99-134 in *Long-Term Studies of Vertebrate Communities*. Academic Press, Inc.

Winston, M.R., Taylor, C.M., and Pigg, J. 1991. Upstream extirpation of four minnow species due to damming of a prairie stream. *Transactions of the American Fisheries Society* **120**, 98-105.

Wolman. 1954. A method of sampling coarse river-bed material. *Transactions of the American Geophysical Union* 35:951-956.

World Commission on Dams (WCD). 2000. *Dams and Development: A Framework for Decision-Making*. www.dams.org

Table 4.1. List of families and species of fish captured in the upper Puerto Viejo River and the Quebradon stream, Costa Rica during 2001-02 as a part of this study. Common names are listed in parentheses.

Family and species
Family Characidae
Astyanax aeneus (sardina)
Bryconamericus scleroparius (sardina)
Family Pimelodidae
Rhamdia nicaraguensis (barbudo)
Rhamdia rogersi (barbudo)
Family Poeciliidae
Alfaro cultratus (olomina)
Poecilia gillii (olomina)
Priapichthys annectens (olomina)
Family Gobiosocidae
Gobiosox nudus (chupapiedra)
Family Cichlidae
Archocentrus septemfasciatus (mojarra)
Archocentrus nigrofasciatus (mojarra)
Astatheros alfari (mojarra)
Parachromis dovii (guapote)
Theraps underwoodi (vieja; moga)
Family Mugilidae
Agonostomus monticola (tepemechin)

Table 4.2. Species presence/absence along the dewatered reach of the Puerto Viejo River. Letters after a species name indicate life history strategies: P=periodic; O=opportunistic; E=equilibrium.

	Downstream distance from dam (m)							
Species	208	1043	1484	2190	2493	2873	3250	4179
Agonostomus monticola (P)	x	x	x	x	x	x	x	x
Astyanax aeneus (O)				x	x		x	x
Gobiosox nudus (O)	x	x	x	x		x	x	x
Poecilia gillii (O)	x	x	x	x	x	x	x	x
Priapichthys annectens (O)			x					
Rhamdia nicaraguensis (O)	x	x	x	x	x	x	x	x
Rhamdia rogersi (O)	x	x	x	x	x	x	x	x
Archocentrus septemfasciatus (E)								x
Astatheros alfari (E)								x
Theraps underwoodi (E)						x	x	
Species Count:	5	5	6	6	5	6	7	8
Estimated species richness:	6	6	7	8	5	8	7	8

Table 4.3. Summary of selected habitat data from sites (a) upstream and downstream from the dam (2001) and (b) at different distances downstream from the dam within the de-watered reach (2002). QQ=Quebradon stream; PV=Puerto Viejo River.

(a)

Site	Approximate distance from dam	Reach length (m)	Average width (m)	Pool habitat (%)	Rapid/riffle habitat (%)	Run Habitat (%)	Temperature (C) max	min	Average depth (cm) pool	rapid	Average velocity (m/s) pool	rapid
QQA	50m upstream	255	13.01	24.93	74.64	0	21.69	18.58	28.57	24.11	0.276	0.38
QQD	50m downstream	204	6.80	58.92	41.08	0	22.31	18.69	14.16	9.54	0.032	0.049
PVA	100m upstream	300	18.56	4.55	69.96	25.49	20.68	17.12	63.12	34.09	0.544	0.665
PVDM	100m downstream	300	12.43	56.77	43.23	0	22.29	17.73	39.88	14.07	0.129	0.156
PVCQ	4000m downstream	300	20.30	50.65	49.35	0	23.62	19.17	20.71	18.89	0.112	0.138
PVCU	6000m downstream	200	19.37	56.15	43.85	0	N/A	N/A	36.90	35.83	0.319	0.51

(b)

Downstream distance from dam (m)	Reach length (m)	Average width (m)	Pool habitat (%)	Rapid/riffle habitat (%)	Temperature (C) min	max	Average depth (cm) pool	rapid	Average velocity (m/s) pool	rapid
208	100	9.89	53.2	46.8	18.41	23.01	42.19	23.09	0.073	0.144
1043	100	10.42	76.3	23.7	-	-	29.68	33.46	0.086	0.224
1484	100	10.24	59.2	40.8	-	-	32.86	19.50	0.065	0.159
2190	100	17.57	65.3	34.7	-	-	14.56	21.20	0.04	0.114
2493	100	14.10	82.8	17.2	19.02	24.15	38.58	31.80	0.116	0.424
2873	100	11.67	69.5	30.5	-	-	42.62	37.45	0.109	0.227
3250	100	13.55	69.8	30.2	-	-	29.59	30.70	0.069	0.199
4179	100	23.68	53.4	46.6	19.36	25.20	24.13	22.05	0.059	0.203

Table 4.4. Characteristics of life history strategies and classification of Puerto Viejo River fishes by strategy. Adapted from Winemiller (1995).

	Opportunistic	**Periodic**	**Equilibrium**
Demographic factors	Juvenile and adult survivorship low and variable; short generation times.	Low and variable juvenile survivorship; adult survivorship high with low variance; Large generation times.	Juvenile and adult survivorship high with low variance; variable generation times.
Physiological factors	Small adult body size; small neonate body size; short-lived.	Large adult body size; small neonate body size; intermediate-long lived.	Variable adult body size; large neonate body size; intermediate-long lived.
Behavioral factors	None-little parental care; long reproductive season; many reproductive bouts per season.	None-little parental care; short reproductive season; One or few reproductive bouts per season.	Parental care; Variable length of reproductive season; One or few reproductive bouts per season.
Environmental factors	Harsh and unstable physical conditions; Variable access to food resources; Predation pressures common.	Patchy or cyclic physical conditions; Food resources vary periodically; Populations may be density-dependent.	Stable or predictable physical conditions; Relatively stable food resources; Populations often density-dependent.
	Puerto Viejo River fishes		
	Poecilia gillii *Rhamdia nicaraguensis* *Rhamdia rogersi* *Astyanax aeneus* *Bryconamericus scleroparius* *Gobiosox nudus* *Priapichthys annectens*	*Agonostomus monticola*	*Astatheros alfari* *Archocentrus septemfasciatus* *Archocentrus nigrofasciatus* *Parachromis dovii* *Theraps underwoodi*

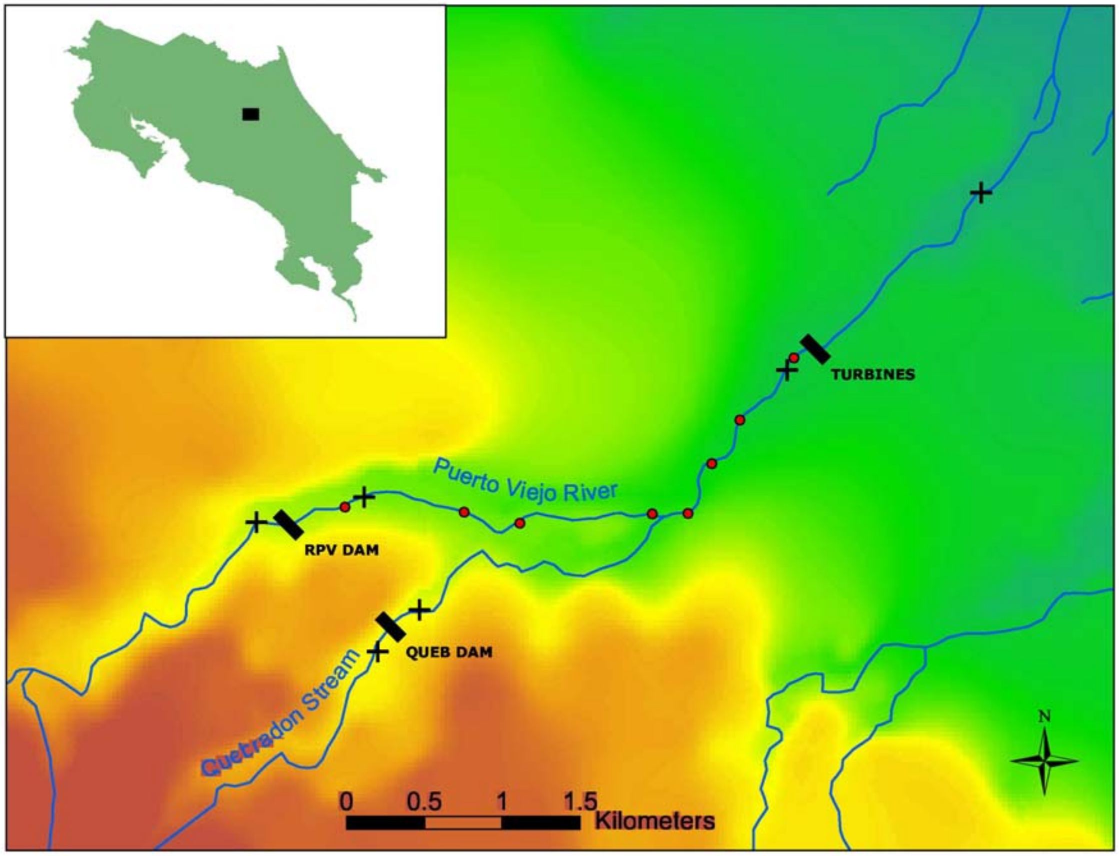


Figure 4.1. The upper Puerto Viejo River and the Quebradon stream are used for hydropower production by the Doña Julia hydropower project. The location of the project's two dams and turbine house are indicated on the map. Our sampling sites are marked on the map with either an **x** (for 2001 sites) or a circle (for 2002 sites). The inset shows the location of the drainage on the northern Caribbean slope of Costa Rica. (Figure prepared by A. Trabucco, Organization for Tropical Studies)

Figure 4.2. Diversion dam on the Puerto Viejo River that is part of the Doña Julia hydropower project. (Photo by EAO, January 2004)

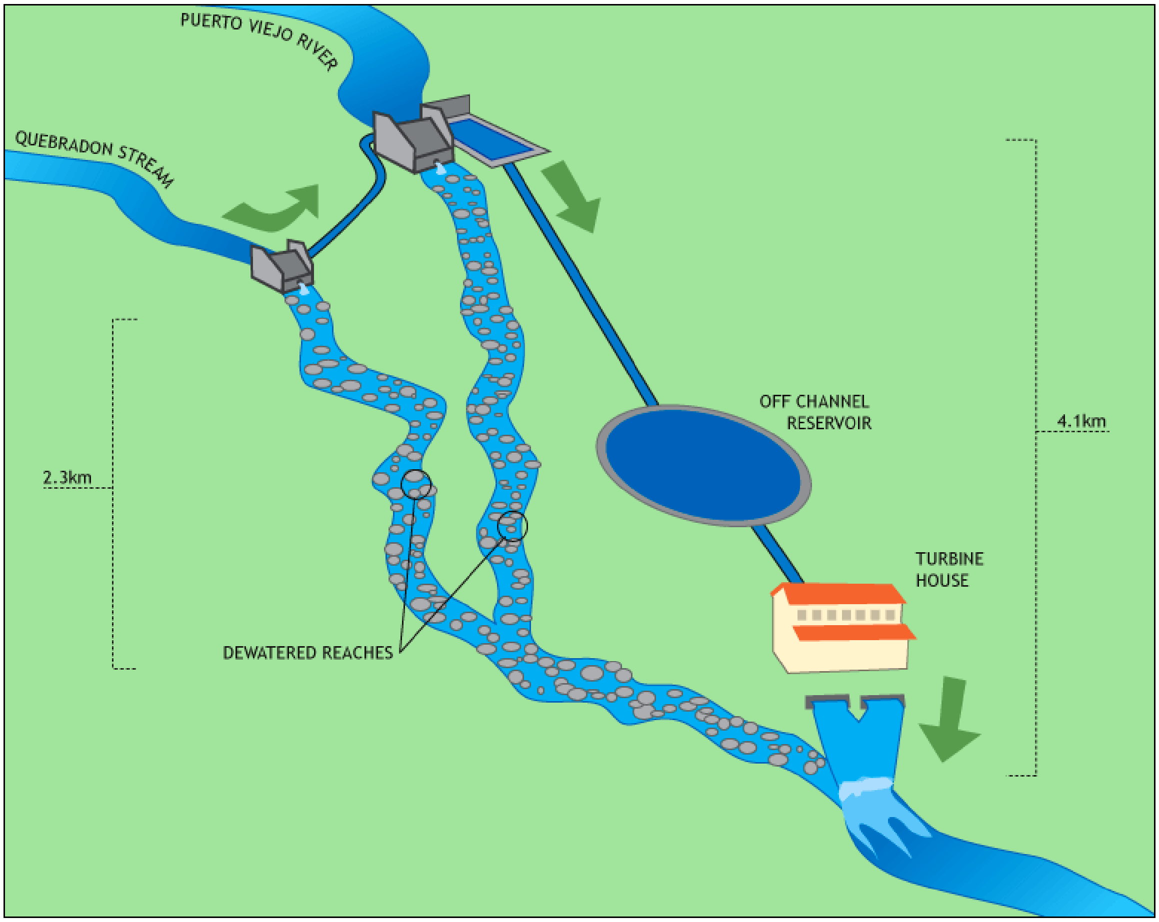
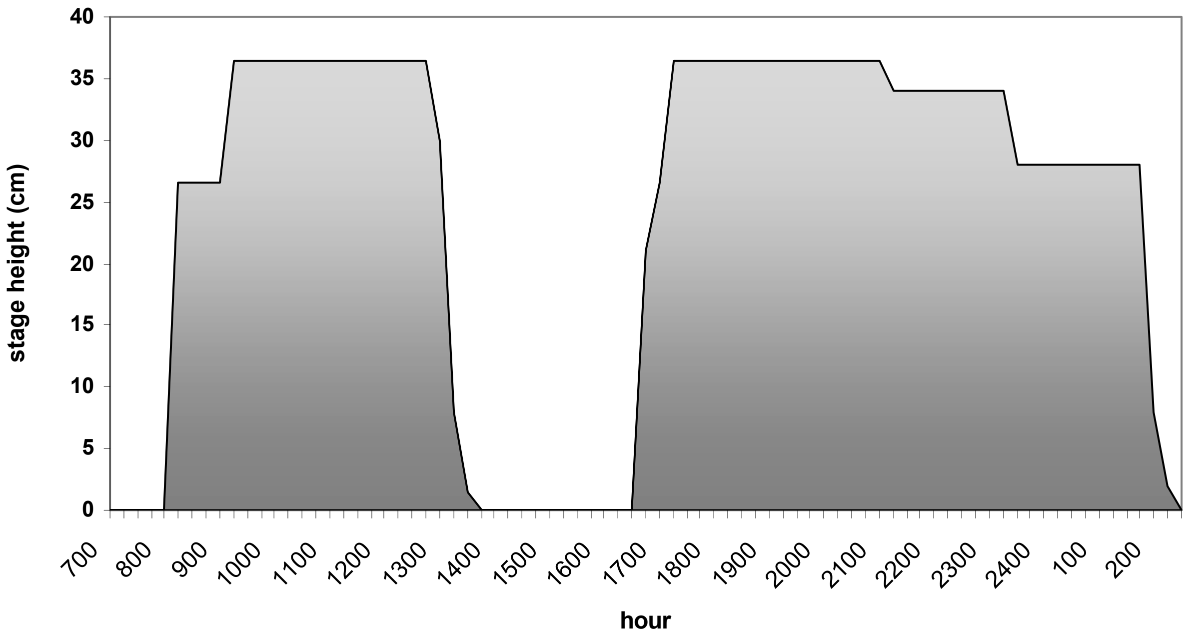
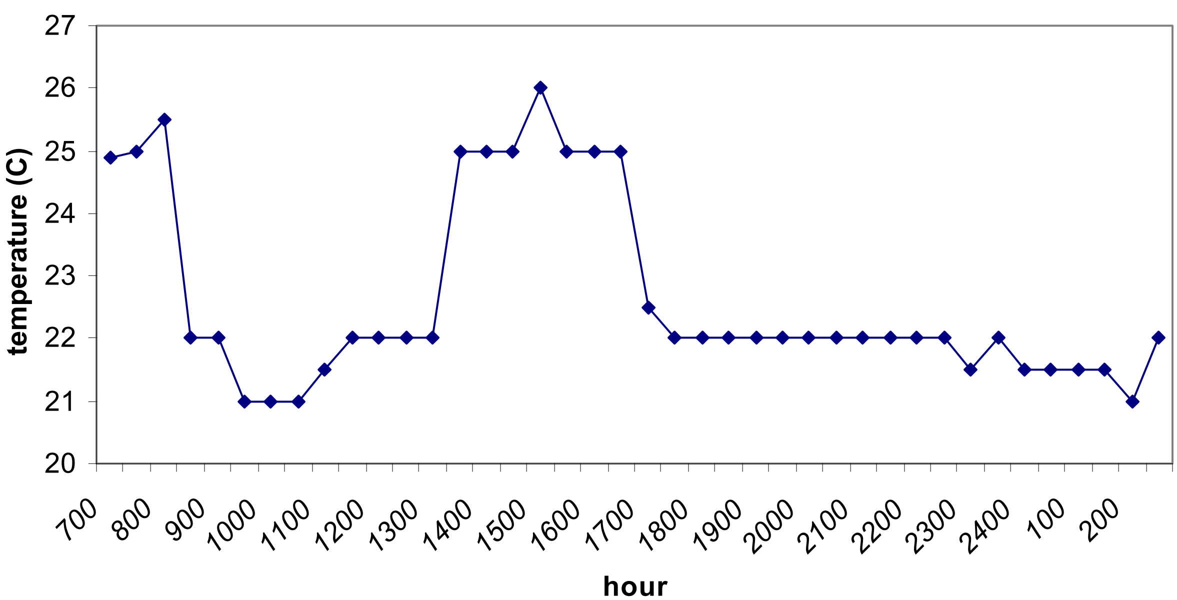


Figure 4.3. Schematic of the Doña Julia Hydroelectric Center. A dam diverts water from the Quebradon stream and sends it via pipeline to the Puerto Viejo River. Water from the Quebradon is diverted along with water from the Puerto Viejo at a dam site on that river. Suspended sediments fall out in a settling tank before water is sent via tunnel and pipeline to an off-channel reservoir with a volume of 80,000 m³. Water is stored in the reservoir until peak hours of generation, when it is pumped via pipeline down an elevation gradient of ~100 m to a turbine house. After being used to generate electricity, water is returned to the river. (Figure prepared by C. Lowe)

Figure 4.4. Fluctuations in (a) stage height and (b) temperature below the water release from the dam on the Puerto Viejo River. Data were collected over a 19 h period on 4/29/02-4/30/02. No stage changes were expected from 200-700 h on 4/30/02.
(a)



(b)



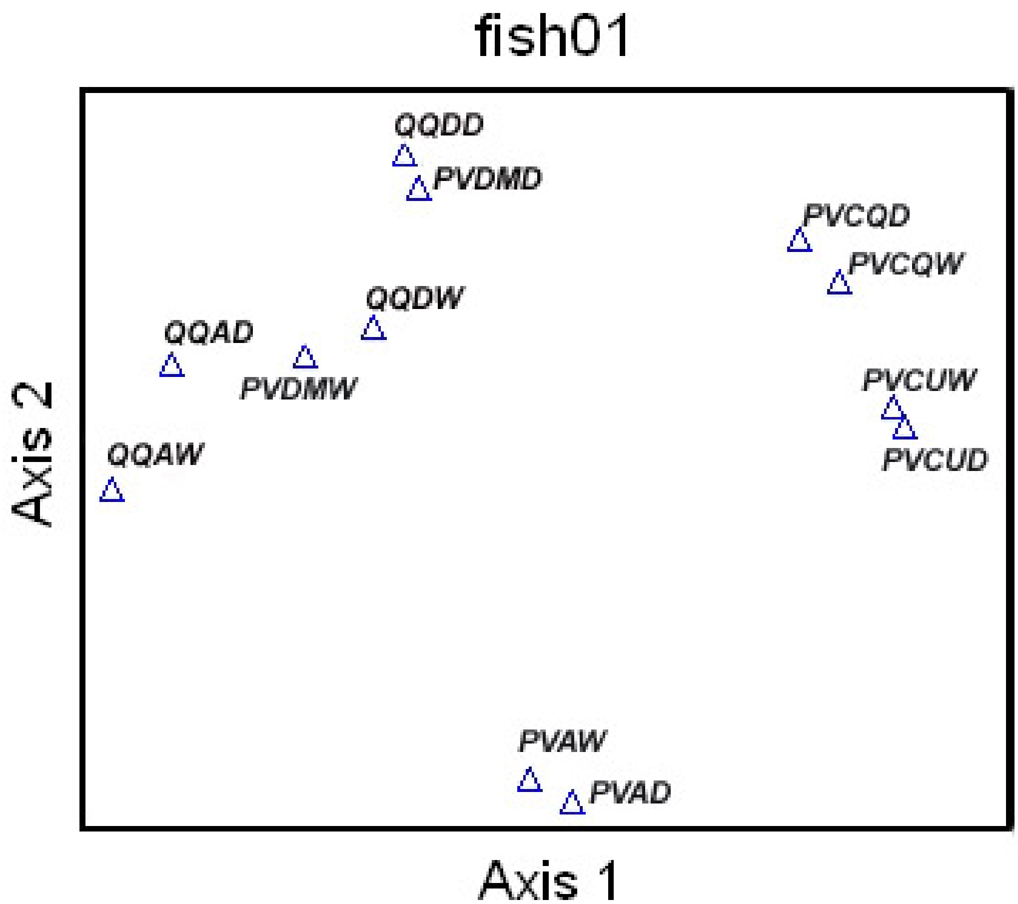


Figure 4.5. The NMS ordination of 2001 fish data shows three distinct groupings according to location: (1) sites on the Quebradon stream (QQA;QQD) and directly below the dam on the Puerto Viejo River (PVDM); (2) sites on the Puerto Viejo River upstream from the dam (PVA); and (3) sites at the end of the dewatered reach (PVCQ) and downstream from the water release (PVCU). D=dry season; W=wet season.

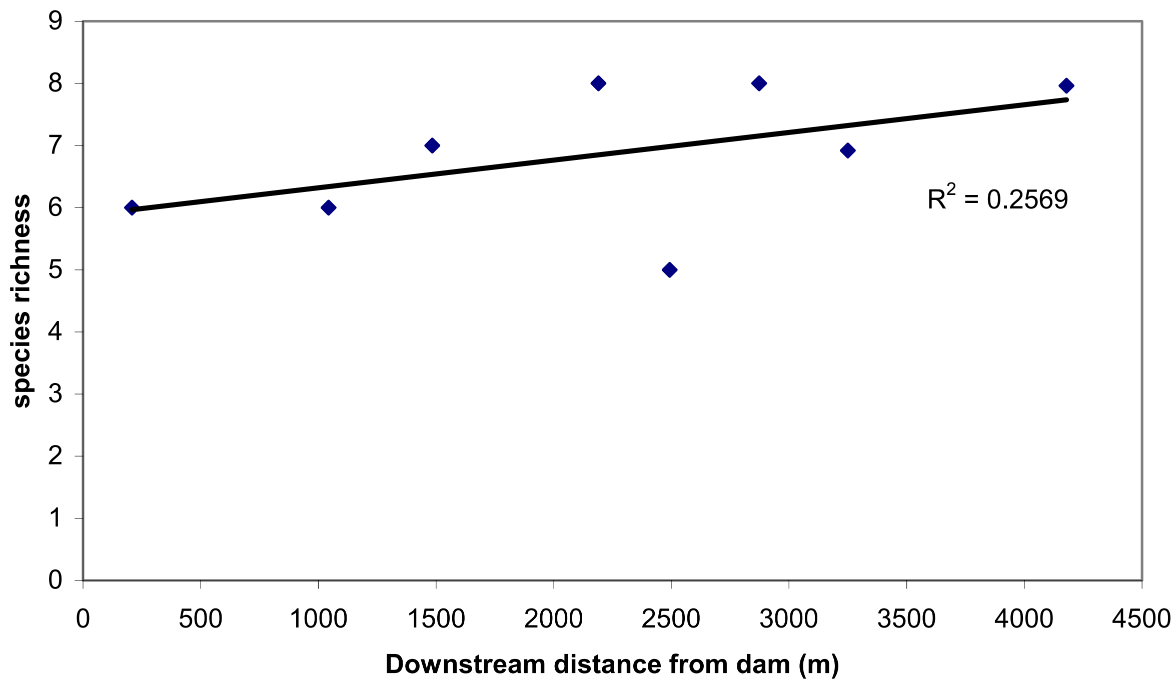


Figure 4.6. Estimated fish species richness with increasing downstream distance from the dam. Data collection was by electrofishing in eight 100 m long transects along the de-watered reach of the Puerto Viejo River.

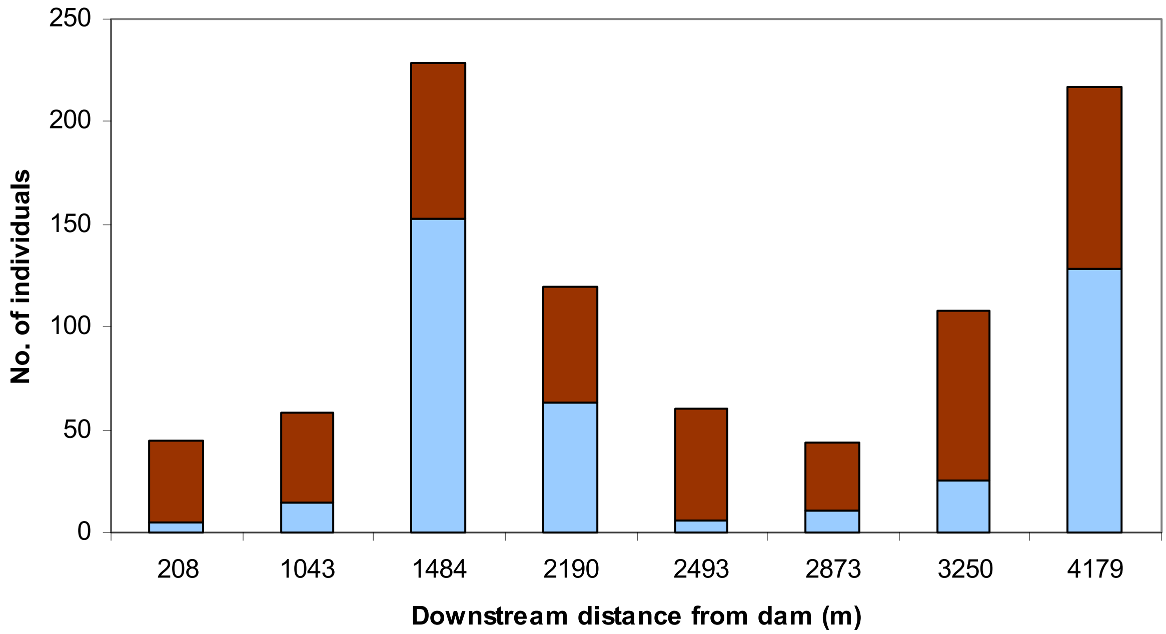


Figure 4.7. Number of individual fish versus downstream distance from the dam on the Puerto Viejo River. The lightly-shaded part of the column represents the number of individuals of *Poecilia gillii* at each site.

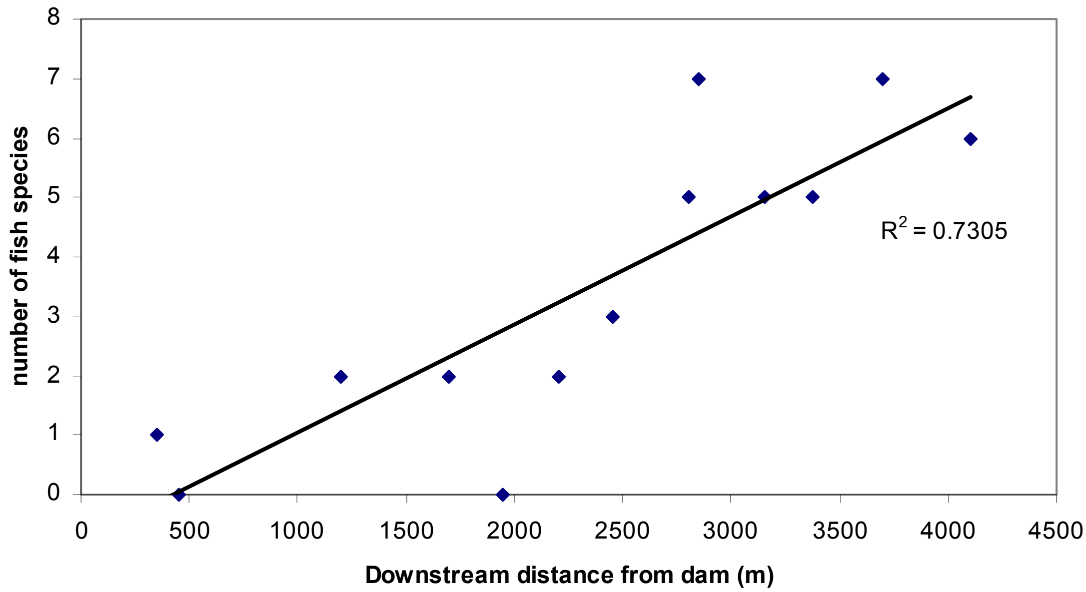


Figure 4.8. Number of fish species in pools vs. downstream distance from the dam along the de-watered reach of the Puerto Viejo River. Data were collected by visual assessments in pools during Jan-Feb 2002.

CHAPTER 5:

HYDROPOWER DEVELOPMENT AS A CATALYST FOR CONSERVATION OF A COMMON-POOL RESOURCE IN SARAPIQUI, COSTA RICA[1]

[1]Olivas, E.A., Pringle, C.M., and Blount, B. To be submitted to Human Ecology

Abstract

The Sarapiquí River, Costa Rica, is a *common pool resource* used by human populations that live and work in its watershed. Human uses of the Sarapiquí and other rivers in the watershed include transportation, tourism (white-water rafting), fishing, potable water, irrigation, and recreation. In addition, hydropower generation has emerged as a major use of rivers in the Sarapiquí since the early 1990s. During less than a decade, eight small hydropower dam projects were constructed on the Sarapiquí River and its tributaries, and additional projects are currently under construction or in planning stages. This recent hydropower development in the watershed has been linked to socio-environmental conflicts, and has been perceived by many local residents as a threat to other human uses of rivers. Hydropower development in Sarapiquí has also been accompanied by increased awareness of the importance of freshwater resources in the lives of local residents as well as an increase in river conservation activities. This chapter documents some of the socio-environmental conflicts associated with hydropower development and examines the role of hydropower as a catalyst for river conservation activities in the Sarapiquí watershed.

Keywords: dams, hydropower, socio-environmental conflicts, common pool resources, watershed conservation, rivers, Costa Rica

Introduction

Hydropower and other types of dam development have been the source of many social and environmental conflicts worldwide (WCD 2000; McCully 1996). These conflicts often result from the complex impacts that dams have on human communities, the natural environment, and interactions between the two. A large body of research documents the social and environmental effects of dams (Goldsmith and Hildyard 1984; McCully 1996; Rosenberg et al. 1997; Horning 1999; WCD 2000); examples of these effects include changes to river flow, alteration of sediment transport, interruption of migration patterns of aquatic biota, reductions of aquatic biodiversity, flooding of forests, and displacement and resettlement of human communities. The past few decades have witnessed the emergence of international organizations dedicated to publicizing and negotiating socio-environmental conflicts associated with dams (e.g., International Rivers Network). Until now, most international attention has focused on large dams, despite the fact that small dams are a more pervasive feature in the global landscape and are also sources of substantial social and environmental conflict in many countries (Benstead et al. 1999; Graf 1999).

The accelerated rate of hydropower dam construction in developing countries has resulted in many dam-related conflicts in Asia, Africa, and Latin America. In Costa Rica, the number of hydropower dams has tripled since the early 1990s; the majority of these dams are small (<15 m high), privately owned, and located in rural areas. These increases in small hydropower development have been linked to a growing number of socio-environmental conflicts over freshwater resources in Costa Rica. At a national level, there appear to be three reasons for these conflicts (Aguilar 2001). First, there is a general absence of integrated planning and protection in watersheds throughout Costa Rica and hydropower is perceived as a major threat to ecological integrity of water resources. Second, the basis for granting freshwater concessions is susceptible to challenge in Costa Rica. Concessions are often based on the demand for (and not the availability) of water resources and hydropower projects compete directly with other users (e.g., tourism, potable water, irrigation, aquatic ecosystems) for freshwater. Problems with the protocol for environmental impact assessment (EIA) are a third source of conflicts, specifically the absence of cumulative effects assessments where multiple hydropower dams are constructed on individual watersheds (Estado de la Nación 1998). The current EIA process in Costa Rica also has been criticized for a lack of clarity in the definition of 'environmental' or 'instream flows' and limited participation of human communities in impact assessments (Aguilar 2001).

In Costa Rica, rivers are public property, and thus, they belong to all residents and can be considered *common pool resources*. Here, we define a *common pool resource* as a valued resource that is accessible or available to more than person and subject to degradation as a result of overuse (Hardin 1968; Dietz et al. 2002). Humans use *common pool resources* as sources of goods or as sinks for unwanted by-products. In this sense, rivers in Costa Rica act as both sources of goods (i.e., fish, shrimps, water, transportation, recreation, hydroelectricity) and as sinks for wastewater and runoff from urban and agricultural lands. Like most water resources, Costa Rican rivers are susceptible to environmental problems related to the over-harvest of goods and overuse as a sink and the 'misuse' of *common pool resources* can be a source of conflicts. These conflicts often stem from two of the defining characteristics of *common pool resources*: costly exclusion and subtractability. In terms of rivers, 'costly exclusion' refers to the idea that it is impossible to put a fence around a river to prohibit use of the resource.

Subtractability refers to the fact that one person's use of a *common pool resource* can reduce the availability of that resource for others (Dietz et al. 2002).

In Costa Rica, the 'subtractability' of rivers has been a major source of socio-environmental conflicts between hydropower developers and residents of areas where dam projects are located. The Sarapiquí River watershed in northeastern Costa Rica provides an interesting case for examining these conflicts. Historically, the Sarapiquí River was a primary link between the Caribbean coast and the interior of Costa Rica. For decades it played a pivotal role in the establishment of human communities on the country's northern Caribbean slope and in the transportation of goods from abroad (e.g., Europe) to the capital, San Jose. Today, the Sarapiquí River is nationally known for its scenic beauty, its wealth of biodiversity, and for the fact that it remains one of a disappearing class of relatively intact rivers in Costa Rica. For rural residents, the river is a *common pool resource* that provides water, food, work, and pleasure. Furthermore, the river continues to influence regional development. Within the last 15 years, eight hydropower dam projects have been constructed on the Sarapiquí River and its tributaries; planning for additional projects is in advanced stages. Accelerated hydropower development has led many rural residents to re-evaluate the river's role in the region and has created concern about how increased damming may compromise the present state of the river and current uses of freshwater. In the last decade, a series of river conservation movements has emerged in Sarapiquí, partly in response to hydropower development. These conservation efforts have resulted in increased awareness of the importance of freshwater resources in the lives of rural residents.

The purpose of this chapter is to document the multiple uses of rivers in Sarapiquí, Costa Rica, and consider these uses of a *common pool resource* (sensu Hardin 1968) in the context of recent hydropower development. The chapter begins by tracing the development history of the Sarapiquí region and outlining the role of the Sarapiquí River in the lives of rural residents. Next, we provide a summary of hydropower development in the Sarapiquí watershed with a brief description of environmental consequences. We then examine conflicts between hydropower and downstream human communities. We also document watershed conservation activities in Sarapiquí and discuss how hydropower development has motivated many of these activities.

The information presented here is based on 20 months of fieldwork from 1999 to 2004. Methods used to collect information included: (1) formal interviews with river users including boat operators, rafting companies, NGOs, water resource managers, the Costa Rican Institute of Electricity (ICE), and dam companies; (2) structured interviews with 100 residents of Sarapiquí County related to perceived importance of different freshwater uses; (3) observations and field notes from participant-observation at town meetings and conservation activities; and (4) hundreds of informal conversations with rural residents over a four year period.

The Sarapiquí River: a river of many uses

The Sarapiquí River drains an extensive area of northern Costa Rica, cutting through a landscape marked by variable topography and land use (Figure 5.1). The river emerges in the highlands from Barva Volcano at 2850 m.a.s.l. and flows for ~85 km in a north-south direction. Dramatic changes in elevation characterize the headwaters of the Sarapiquí, creating a cascading sequence of rapids and plunge pools in an encanyoned channel (Figure 5.2). Natural forest dominates the landscape in the upper Sarapiquí watershed, where the steep topography makes intensive land use activities difficult. As the river descends to middle-elevations (250-1000 m), tributaries increase the flow and the power of the river. Present land uses in this region include cattle pastures, pineapple agriculture, and tree plantations, interspersed by remnant patches of natural forest (Figure 5.3). The Sarapiquí widens as it flows into the lowlands and is joined by two important tributaries: the Puerto Viejo River and the Sucio River. Once in the lowlands, the river slowly meanders through a mosaic of agricultural lands, banana plantations (Figure 5.4), and rural human settlements before draining into the San Juan River at the Nicaraguan border.

While the last 50 years have brought major social and environmental changes to the Sarapiquí region, the river has maintained a central role in the lives of rural residents (Table 5.1). Until the middle of the last century, the Sarapiquí region was one of the last frontiers of Costa Rica. Mule trails and the Sarapiquí River, navigable downstream from Puerto Viejo, were the only connections between the region and the outside world until the 1950s, when the dirt road between San Jose and Cariblanco was extended to Puerto Viejo (Butterfield 1994). The new road increased the regional importance of the river and the town of Puerto Viejo: products from the Caribbean coast and the Nicaraguan border were shipped by way of the Sarapiquí River to Puerto Viejo and then continued via truck to San Jose. From 1963-1983, the colonization of the frontier resulted in an increase in the region's population from 4,856 to 18,909 inhabitants and a decrease in forested area from 70% to 30% as settlers converted much of the land to pasture (Table 5.1; Butterfield 1994). The Sarapiquí River also gained importance during this time, providing a source of potable water, food (fish and freshwater shrimp), transportation, and recreation for rural residents. Expansion of banana agriculture along the banks of the lower Sarapiquí River during the late 1980s and early 1990s also affected the river, as banana companies drew water from wells and built drainage canals to carry precipitation runoff, laden with agricultural chemicals, to rivers (Vargas 1995). The late 1980s and early 1990s were also a period of marked population increase in Sarapiquí, primarily due to immigration of banana plantation workers to the region (Table 5.1). These population increases, coupled with deforestation and agricultural development in the region, put additional pressures on potable water supplies by decreasing the water quality of the Sarapiquí River near Puerto Viejo. As a result, many residents turned to springs and small streams inside of Braulio Carrillo National Park for their water supply (Vargas 1995).

Since the early 1990s, the region has experienced a steady increase in population. Most forests not in protected areas (e.g., national parks or private reserves) have been converted to agricultural lands or human settlements. An estimated 45,000 inhabitants now live in Sarapiquí County (Figure 5.5; INEC 2004); the Sarapiquí River remains a river of many uses for these residents. Recreation is still at the forefront of current uses of the river: on any Sunday or holiday people flock to the river to picnic along its banks and swim in its waters (Figure 5.6). The river is also commonly used for recreational and subsistence fishing, especially in the lowlands where it supports a diverse assemblage of fishes and other aquatic biota (Bussing 1993). In addition, the Sarapiquí River attracts both national and international tourists as the site for a growing whitewater rafting industry in the mid-reaches, and a scenic nature cruise business in the lowlands (Figure 5.7).

The Sarapiquí River is also a source of cultural identity for rural residents of Sarapiquí County. Perhaps this identity is strongest for long-term inhabitants of the region, especially those who were born there and grew up dependent on the river as their principal source of water. Orlando Vargas, 36, a life-long resident of Sarapiquí, describes the basis for this cultural identity:

> "Yo crecí a la par del Río, fue para mi familia el principal recurso acuífero; pesqué, crecí, y aprendí a nadar en este Río." *Translation: I grew up on the banks of the River, for my family it was the principal water resource; I fished, grew up, and learned how to swim in this River.*

Juan Hernandez, 47, who identifies himself as a farmer and is also native to the region, elaborates on the role the Sarapiquí River has played in his life:

> "Soy nativo, 100% Sarapiqueño. He vivido de la navegación, la pesca, en el Río aprendí a nadar. Mis abuelos habían disfrutado del Río Sarapiquí. Ahora hay muchos de nosotros que trabajan en el turismo. Quiero protegerlo (el Río) para futuros generaciones." *Translation: I'm native, 100% Sarapiqueño. I have lived off of transportation, fishing, and in the River I learned to swim. My grandparents enjoyed the Sarapiquí River. Now, there are many of us that work with tourism. I want to protect (the River) for future generations.*

The combination of cultural identity and profound knowledge of the river has created a sense of ownership of the river among older Sarapiquí residents. This sense of ownership has helped transform long-term residents of the region, many of whom once regularly hunted rainforest mammals and exploited river fisheries, into a conservation-minded group, vigilant about environmental problems and changes in the region. It also has motivated the grassroots organization of community conservation groups and activities to protect or clean up the Sarapiquí River. One example is the Association for the Environmental Health of Sarapiquí (ABAS), dedicated to working against environmental pressures in the region. The ABAS was formed during the 1990s by local residents and naturalist guides that were concerned about deforestation in the region and wanted to preserve forested lands and start reforestation programs (J. Alvarado, personal communication). Since then, the ABAS has been instrumental in identifying environmental issues in the region, in particular those related to water resources. A recent campaign sponsored by ABAS was the posting of signs with the names of rivers and information about the watershed near bridges around Sarapiquí (Figure 5.8). The idea behind ABAS's campaign was that once people know the names of rivers, they will form a more intimate relationship with their landscape that may encourage conservation of these resources.

Hydropower development in the Sarapiquí River watershed

In the past two decades, hydropower has emerged as a principal user of freshwater in the Sarapiquí River watershed and throughout Costa Rica (Estado de la Nación 1998). The discussion here merits a brief examination of the role of hydropower on a national level before we focus on hydropower development in Sarapiquí. Unlike most developing countries, in Costa Rica, approximately 97% of residents have electricity in their homes (R. Jimenez, ICE, personal communication). Hydropower generates roughly 85% of this electricity; thermal, geothermal, and wind plants account for the rest. Much of Costa Rica's hydropower potential currently remains untapped, although plans for meeting increases in the demand for electricity, estimated at roughly 6% annually, include the construction of more and bigger dams over the next decade.

Since the institution's creation in the 1940s, the government-owned Costa Rican Institute of Electricity (ICE) has been charged with developing the country's energy resources to satisfy increasing demands. The ICE currently operates ~15 hydropower projects with a combined total installed generating capacity of approximately 1000 megawatts. Two of these projects are located on the Toro River, a principal tributary of the Sarapiquí River. During the 1990s, increasing demands on the ICE led to the passage of two laws (Ley 7200 in 1990 and Ley 7508 in 1995) that opened Costa Rica's electricity sector to private generators. As a result, private companies are now permitted to generate 15% of Costa Rica's electricity and sell it to the ICE at fixed prices. Hydropower developments in the Sarapiquí watershed and many other areas of Costa Rica can be directly linked to this partial privatization of electricity generation in the 1990s. Between 1990-2000, ~28 private hydropower plants were constructed on Costa Rican watersheds; six of these private plants are located on the Sarapiquí River or its tributaries.

A total of eight hydropower plants are currently in operation in the Sarapiquí watershed, and additional projects are being planned (Table 5.1). With a hydropower potential estimated at around 390 megawatts, of which only 144 have been exploited, the Sarapiquí watershed remains a principal target for hydropower developers in Costa Rica. Several things make Sarapiquí appealing from a developer's perspective. First, the region's climate is extremely wet (4-8 m annual rainfall) and less seasonal than in other parts of Costa Rica (Sanford et al. 1994). Thus, streams in the Sarapiquí watershed carry sufficient discharge almost year-round for hydropower generation. Second, the steep topography of the upper watershed is characterized by abrupt changes in elevation. Hydropower projects can take advantage of this high geographic relief as a way to increase 'hydraulic head' or 'water power' and generate more electricity from less water. Moreover, the geographic location and the road network of the Sarapiquí region increase the watershed's accessibility to hydropower developers. Sarapiquí is roughly a 1.5-2 hour drive from San Jose, the Costa Rican capital and business center. Well-maintained, paved roads connect the region with the capital.

All hydropower projects in the Sarapiquí watershed are located on or near elevational gradient breaks and operate as water diversion dams (Figure 5.9). A major environmental impact of these types of projects is the substantial reduction of stream flows between the water diversion site and the turbines / water return site. These flow reductions are often referred to as stream 'dewatering.' In Sarapiquí, hydropower projects divert 90-95% of the flow from rivers with dams; the operation of eight hydropower projects has resulted in the dewatering of ~31 kilometers of streams throughout the watershed. An additional environmental impact of hydropower projects in Sarapiquí is the unnatural fluctuations in stream flows that occur downstream from the turbines / water return sites. Most projects operate on a peaking-power schedule, generating electricity twice daily during hours of high demand. The results are rapid changes in flow and temperature that may create inhospitable habitat conditions for aquatic biota. These flow changes also present flash-flood like conditions that are dangerous to downstream water users like swimmers, rafting tourists, or fishermen. Many hydropower companies have posted signs to warn downstream human communities of this danger (Figure 5.10).

Conflicts and the commons

In the late 1990s, perceived 'subtractions' or reductions in the quantity and quality of river water after the construction of several hydropower projects alarmed downstream communities near the towns of La Virgen and Puerto Viejo de Sarapiquí. Specifically, people started to report changes in channel geomorphology and greater and more frequent fluctuations in the flow of the Sarapiquí and other rivers. These alterations were viewed as a threat to economically important activities in the region, especially river-related tourism (e.g., white-water rafting, tour boats). They also threatened recreational uses of rivers, as fluctuations in flow make these uses dangerous.

A socio-environmental conflict exploded in 1998, when ABAS and other social organizations in the region learned of plans to build a hydropower project on the Sarapiquí River near La Virgen (Merida, S.A. 1998; Aguilar 2001). This project would have substantially compromised other uses of the river because it would have been located directly upstream from principal recreational and tourism areas. In response to the development pressures of the La Virgen and other hydropower projects, a coalition was formed to 'defend' the Sarapiquí River (known as the *Colectivo para la Defensa del Río Sarapiquí*). This coalition comprised multiple social and environmental groups from the region. The coalition organized public demonstrations and posted fliers to inform the community about hydropower development (Figs. 5.11, 5.12, and

5.13), with the central goal of protesting construction of more hydropower projects in the Sarapiquí watershed (Aguilar 2001).

A major contribution of the coalition was the organization of a popular vote, or *plebescito*, that permitted rural residents to express their desires to conserve the Sarapiquí River watershed. Under the direction of the Municipality of Sarapiquí, the *plebescito* was held on 24 September 2000 with a voter turnout of 2,254 people, which was <15% participation. Voters were asked to respond to the following question with a 'yes' or 'no' answer:

> "Esta Ud. de acuerdo en conservar el Río Sarapiquí solicitando la declaratoria de su cuenca como Monumento Histórico Natural?" *Translation: Are you in favor of the conservation of the Sarapiquí River by soliciting the declaration of its watershed as a Natural Historic Monument?*

Voter turnout was low, but the overwhelming majority (~90%) voted 'yes' for the conservation of the watershed (Loaiza and Vasquez 2000). Although the question did not explicitly mention hydropower development in the region, at a national level the results of the *plebescito* were taken to mean that the Sarapiquí community was opposed to further construction of hydropower projects in the watershed (Aguilar 2001). One of the greatest successes of the *plebescito* was that it identified rural residents as 'stakeholders' and brought a formality to the socio-environmental conflict in the Sarapiquí watershed. As a follow-up, the Municipality of Sarapiquí named a commission (known as the *Comisión de Seguimiento al Plebescito*) made up of Sarapiquí's residents, representatives from the ICE, and regional officers from the Minister of Environment and Energy (MINAE). The primary objectives of the commission were to: (1) work towards the declaration of the Sarapiquí River as a Natural Historic Monument in Costa Rica; and (2) oversee and solict funds to develop an integrated management plan for the watershed (Aguilar 2001).

To date, the Sarapiquí River has not legally been declared a Natural Historic Monument. In addition, many of the original organizations dedicated to protesting hydropower development in Sarapiquí are no longer actively involved in the socio-environmental conflict. In fact, the ABAS has emerged as the main advocate for conservation of the Sarapiquí watershed and appears to be one of the only organizations still actively protesting future hydropower development. ABAS' most recent campaigns against hydropower in the watershed involve the Cariblanco Dam, a 80-megawatt, large dam (>15 m tall) proposed by the ICE for the mainstem Sarapiquí River between the towns of Cariblanco and San Miguel, just outside the southern limits of Sarapiquí County (Figure 5.1). Construction of this dam is slated for 2004-06 and its operations likely will result in substantial changes to the hydrology of the Sarapiquí River. Ideally, ABAS would like to halt the hydropower project altogether. However, since it appears that the Cariblanco Dam will go ahead as scheduled, a more realistic approach to the conflict may be to demand more comprehensive surveys of aquatic biota near the project site prior to, during, and following construction to document the actual impacts of the project on Sarapiquí River fauna. Furthermore, downstream water users should pressure the ICE to leave sufficient flows to maintain current human uses of the river.

What is noteworthy about the conflict over the Sarapiquí River is that it has stemmed almost entirely from hydropower developments, whereas other human activities in the watershed may have greater social and environmental effects. Poor management of wastewater, deforestation of riparian areas, over-fishing, and agricultural expansion are all activities with substantial impacts on the ecological integrity of the watershed. Banana agriculture, for example, has been linked to fish kills, substantial decreases in water quality, and problems with sedimentation in the Sarapiquí River. However, there have been few or no organized efforts to protest these activities in Sarapiquí. Why haven't these activities attracted the same local response as hydropower development? One reason may be that local residents are often the ones responsible for deforestation of riparian areas and overfishing. Furthermore, in terms of agricultural expansion, a substantial percentage of the current population immigrated to the region to work on the large banana plantations and throughout the past decade, banana plantations have been the largest employer in the region. Thus, it is likely that local residents view banana agriculture as a beneficial activity, despite its environmental costs.

Isaias Alvarado, 66, a life-long resident of the region, expresses his thoughts on human activities in the watershed:

> "Yo siento que la comunidad puede sacar materials del Río para la comunidad. Pero algo commercial…no debe ser." *Translation: I feel that the community can take things from the River for the community. But, something commercial…I don't agree with that.*

The Sarapiquí community's perception of the river as a *common pool resource*, alluded to in this comment, signifies that it is the community's resource to protect or pollute. Since all hydropower projects in the watershed belong to individuals or companies from other parts of Costa Rica (and in many cases from other countries), in this sense, hydropower development is an activity imposed from the outside that may not fall within local residents' accepted uses of rivers as *common pool resources*. If the Sarapiquí community had perceived some benefits to hydropower development for the community, their opposition to hydropower might not have materialized into the socio-environmental conflict described here. However, many local residents believe that hydropower development brings no advantages for rural residents apart from the temporary jobs created during a project's construction phase. In addition, electricity from hydropower projects in Sarapiquí is exported to the national electrification system of Costa Rica and then distributed to various parts of the country. Joel Alvarado, 40, a naturalist guide and native to the region, when asked if there were any advantages of hydropower development for Sarapiqueños replied:

> "Not for us…in terms of jobs, there are many during the construction phase but after that you only need five people or so to operate a dam. Also, even though we are supplying a lot of electricity, it goes to San Jose (the capital) or somewhere else. We don't get a cheaper price either."

Perceived importance of rivers to the Sarapiquí community

As a follow-up to the conflicts, we conducted 100 structured interviews with residents of Sarapiquí County in 2003-04 to document the perceived importance of different uses of rivers in Sarapiquí. Interviews were conducted by two investigators in the principal towns of the three major districts of the county (La Virgen, Horquetas, and Puerto Viejo; Figure 5.5). Eight interviews were also conducted in the town of San Miguel, just outside of the county line but within the watershed. One of the investigators was a local resident of Puerto Viejo with training in survey methods; the other was a foreign resident of Costa Rica who had been working in Sarapiquí for several years. The number of interviews per region was based on relative population density and the investigators selected participants haphazardly while walking around the towns. Participants were given 9 test cards, each representing one of the major uses of rivers in Sarapiquí: tourism, transportation, fishing, wastewater drainage, recreation, hydropower, irrigation, potable water, and scientific research. They were then asked to put the cards in order according to the importance of each use to the Sarapiquí community. After ranking uses of rivers in terms of importance, participants were asked to rank the cards according to the damage that they thought each use caused the environment. Those uses perceived as causing more environmental damage to rivers were ranked first.

Tourism was perceived, on average, as the most important use of rivers in Sarapiquí, since the tourism industry provides many of the jobs in the region (Table 5.2). Community usage of rivers for transportation, potable water, and recreation followed tourism in perceived importance. On average, hydropower ranked 7th in importance among freshwater uses. However, among respondents from the town of San Miguel, hydropower was considered to be 3rd in importance, after tourism and transportation. Of the four towns included in this study, San Miguel is the closest to existing hydropower developments and is near the site for the new Cariblanco hydropower project.

Wastewater drainage was perceived as the most environmentally damaging of uses of the Sarapiquí River, followed by hydropower (Table 5.2). This is noteworthy because all hydropower developments in the watershed are located several kilometers (10 or more) upstream from all of the towns except San Miguel. Moreover, the vast majority of the people interviewed had never visited a hydropower plant. It is likely that hydropower's high rank on the list of uses that cause environmental damage stems in part from the socio-environmental conflicts associated with hydropower development in the watershed in recent years.

River conservation in Sarapiquí

Ironically, hydropower development of the Sarapiquí watershed has been accompanied by an increase in river conservation activities in the region. The ABAS campaign to post the names of rivers along their banks provides one concrete example. The realization of the *plebescito*, where residents were asked to vote for the conservation of the Sarapiquí River, is another good example of the growing awareness of the importance of rivers to human communities in Sarapiquí. Smaller conservation projects (e.g., frequent trash collecting boat trips along the margins of the Sarapiquí River) have also become common over the past few years. Furthermore, during 2001-2002, several workshops were held in the region to discuss research and management needs for the Sarapiquí watershed. These workshops involved representatives from the Costa Rican government (ICE, MINAE, and the Municipality of Sarapiquí) as well as other national and international organizations (Organization for Tropical Studies, FUNDECOR, the World Bank, and ABAS). The ultimate goal of these workshops was to develop a management plan for the Sarapiquí watershed; as of early 2004 this work is still in progress.

Promoting and implementing integrated watershed management represent two distinct challenges, as do advocating river conservation and actually making it work. Whose responsibility is river conservation and management in the Sarapiquí watershed? Is this the job of the national or municipal government? Or should it be left up to local residents of Sarapiquí to decide the fate of rivers as *common-pool* resources in the region where they live? Joel Alvarado, a naturalist at La Selva Biological Station and lifetime resident of Sarapiquí, believes that river conservation and management should be a shared responsibility. He challenges the government with creating and enforcing laws that promote conservation of freshwater resources like the Sarapiquí River; residents of the region can best help with conservation by respecting these laws. Many people in Sarapiquí believe that good laws already exist to protect water quality and aquatic biota. Examples include the Forestry Law, which recommends a minimum 30-meter riparian buffer along waterways, as well as other laws designed to regulate fishing methods. However, compliance with these laws has long been an issue in Sarapiquí and throughout Costa Rica. For example, the denuded banks along the lower reaches of the Sarapiquí River downstream from the confluence with the Sucio River (Figure 5.14) illustrate problems with enforcement of riparian buffers. Disrespect for fishing laws is also an issue in the watershed. Park guards from La Selva Biological Station estimate that 90% of the fishing that occurs in the watershed is illegal. Violations of acceptable fishing methods are particularly rampant, and many people use chemicals and explosives as a way to kill many fishes and shrimps at once (Edwin Paniagua, personal communication). Compliance with and better enforcement of existing laws will be the first step towards integrated watershed management and river conservation in Sarapiquí.

What is the role of hydropower in the management and conservation of the Sarapiquí watershed? Should hydropower developers be responsible for promoting wise use of freshwater resources? Should they be a major player in watershed management decisions? Are they obligated to give something back to downstream human communities in exchange for their use of a *common pool resource*? Thus far, conflicts over hydropower development have been a catalyst for river conservation activities in Sarapiquí, yet the participation of hydropower developers in these activities has been limited. Perhaps hydropower developers' greatest contribution to overall watershed conservation to date has been maintenance of forest cover and reforestation of river margins upstream from dams. Two hydropower plants in Sarapiquí have actually established a contract to pay for environmental services provided by rural landowners that maintain forest cover in the watershed upstream from dams (Jorge Dengo, Energía Global, personal communication). In the future, hydropower developers can aid in conservation of the watershed by encouraging and sponsoring similar reforestation and forest protection programs in downstream areas. In addition, hydropower developers in Sarapiquí should be obligated to promote and finance scientific research on the impacts of diversion dams on stream ecosystems.

Conclusions

The Sarapiquí case study is representative of issues facing many watersheds throughout Costa Rica—rapid river development, increased competition among freshwater users, and a growing desire to protect *common pool resources*. It is likely that socio-environmental conflicts over rivers in Costa Rica will only become more common as the country invests more in hydropower to fuel development in the future. Defining the roles of stakeholders and recognizing rivers as *common pool resources* will be an important tactic for negotiating these conflicts, as will a shift towards more integrated watershed management.

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Literature Cited

Aguilar, A. 2001. El conflicto por el desarrollo hidroelectrico de la cuenca del Río Sarapiquí, Costa Rica. CEDARENA. San Jose, Costa Rica. (http://www.cedarena.org/hidrico/docs/Sarapiqui.doc)

Benstead, J.P., March, J.G., Pringle, C.M., and Scatena, F.N. 1999. Effects of a low-head dam and water abstraction on migratory tropical stream biota. Ecological Applications 9, 656-668.

Bussing, W.A. 1993. Fish communities and environmental characteristics of a tropical rain forest river in Costa Rica. Revista de Biología Tropical 41:791-809.

Butterfield, R.P. 1994. The regional context: Land colonization and conservation in Sarapiquí. Pages 299-306 in McDade, L.A., Bawa, K.S., Hespenheide, H.A., and Hartshorn, G.A. La Selva: Ecology and Natural History of a Neotropical Rain Forest. University of Chicago Press, Chicago.

Dietz, T., Dolsak, N., Ostrom, E., and Stern, P.C. 2002. The drama of the commons. Pages 3-36 in: Ostrom, E., Dietz, T., Dolsak, N., Stern, P.C., Stonich, S., and Weber, E.U. (eds). The Drama of the Commons. National Academy Press, Washington, DC. 521 p.

Estado de la Nación (Costa Rica). 1998. Estado de la Nación en Desarrollo Humano Sostenible. San Jose, Costa Rica. Informe 4.

Goldsmith, E. and Hildyard, N. 1984. The social and environmental effects of large dams. Wadbridge Ecological Centre, Camelford. 2 volumes.

Graf, W.L. 1999. Dam nation: A geographic census of large American dams and their hydrologic impacts. Water Resources Research 35:1305-1311.

Hardin, G. 1968. The tragedy of the commons. Science 162: 1243-1248.

Horning, J.F. 1999. Social and Environmental Impacts of the James Bay Hydroelectric Project. McGill-Queen's Press, Montreal. 169 pp.

Instituto Nacional de Estadísticas y Censos (INEC). 2004. Results of the IX National Census for Costa Rica. http://www.inec.go.cr.

Loaiza, V. and Vasquez, C. 2000. Sarapiquí dijo 'si' al Río. La Nación, 25 September.

Merida, S.A. 1998. Estudio de Impacto Ambiental del Proyecto Hidroeléctrico La Virgen. Escazu, Costa Rica.

McCully, P. 1996. Silenced Rivers: The Ecology and Politics of Large Dams. Island Press, Washington, D.C.

Rosenberg, D.M., Berkes, F., Bodaly, R.A., Hecky, R.E., Kelly, C.A., and Rudd, J.W.M. 1997. Large-scale impacts of hydroelectric development. Environmental Review 5:27-54.

Sanford, R.L., Paaby, P., Luvall, J.C., and Phillips, E. 1994. Climate, Geomorphology, and Aquatic Systems. Pages 19-33 in McDade, L.A., Bawa, K.S., Hespenheide, H.A., and Hartshorn, G.A. La Selva: Ecology and Natural History of a Neotropical Rain Forest. University of Chicago Press, Chicago.

Vargas, R.J. 1995. History of Municipal Water Resources in Puerto Viejo de Sarapiquí, Costa Rica: A Socio-Political Perspective. Master's thesis, University of Georgia.

World Commission on Dams (WCD). 2000. Dams and Development: A Framework for Decision-Making. http://www.dams.org.

Table 5.1. Chronology of population growth, changes in land use, and hydropower development in Sarapiquí, Costa Rica.

Decade	Human population	Land-use change	Hydropower development	Conservation activities
1950-1960	< 5000	Forest cover = 70%; Roads extended to Puerto Viejo; Subsistence agriculture		
1960-1970	1963: 4,856 inhabitants	Frontier colonization; Forest cleared for cattle pastures		La Selva Biological Station founded by Leslie Holdridge and the Organization for Tropical Studies
1970-1980	Population growth	Frontier colonization; Forest cleared for cattle pastures		
1980-1990	1983: 18,909 inhabitants and growing	Forest cover = 30% Continued forest clearing; Large banana companies arrive in Sarapiquí	ICE completes a plan for exploiting the hydropower potential of the Sarapiqui watershed	
1990-2000	1990s: rapid population growth and immigration of farm workers from Nicaragua and other parts of Costa Rica	Rapid expansion of banana agriculture; expansion of other crops such as heart of palm and ornamental plants	Eight hydropower plants are constructed in the watershed; additional plants are proposed; Conflicts over hydropower emerge in the late 1990s	ABAS is formed by local residents and naturalist guides; Opposition to hydropower development in the late 1990s
2000-present	2004: estimated 45,000 inhabitants of Sarapiquí County	Expansion of pineapple agriculture	Cariblanco hydropower project begins construction; General hydro project plans finalized	Community vote (*plebescito*) held in 2000; Attempt to declare Sarapiquí River a 'Natural Historic Monument'; Signs posted with names of rivers, trash pick up along river banks

Table 5.2. Hydropower plants in operation in the Sarapiquí River watershed.
Source: ICE, Dept. de generacion privada; ICE, Dept. de proyectos hidroelectricos.

Name	**River**	**General location**	**Size (MW)**	**Began operation**	**Ownership**
PH El Angel	Rio Angel Rio Sarapiquí	Cinchona	3.9	1991	Private
PH Suerkata	Rio Sarapiquí	Vara Blanca	2.7	1995	Private
PH Don Pedro	Rio San Fernando	San Miguel	14.0	1996	Private
PH Volcan 3x	Rio Volcan Rio Volcancito	San Miguel	17.0	1997	Private
PH Dona Julia	Rio Puerto Viejo Q. Quebradon	Cubujuqui	16.0	1999	Private
PH Rio Segundo	Rio Segundo	Bajos del Toro	0.7	1998	Private
PH Toro I	Rio Toro	Bajos del Toro	23.2	1995	Public (state-owned)
PH Toro II	Rio Toro Quebrada Gata Rio Poza Azul Rio Claro	Bajos del Toro	65.9	1996	Public (state-owned)
TOTAL			**143.4**		

Table 5.3. Results of formal interviews where 100 residents of Sarapiquí County were asked to rank (1-9) the following uses of river in terms of importance to the community and perceived environmental damage. Lower rank numbers or scores indicate (a) more important uses or (b) uses that are perceived to be more damaging to the environment. Standard deviations of average scores (1-9) are reported in parentheses.

Human use of rivers	**Rank: Perceived importance**	**Average score: Perceived importance**	**Rank: Perceived env'tl damage**	**Average score: Perceived env'tl damage**
Tourism	1	3.03 (2.01)	7	6.04 (1.77)
Transportation	2	3.72 (1.85)	3	3.92 (1.54)
Potable water	3	3.88 (2.66)	9	7.54 (1.59)
Recreation	4	4.10 (2.27)	6	5.30 (2.09)
Scientific research	5	5.03 (2.22)	8	7.47 (1.66)
Fishing	6	5.29 (2.07)	4	4.56 (2.08)
Hydroelectricity	7	5.52 (2.25)	2	3.56 (2.21)
Irrigation	8	6.16 (2.11)	5	4.63 (2.32)
Wastewater drainage	9	8.25 (1.43)	1	1.69 (1.52)

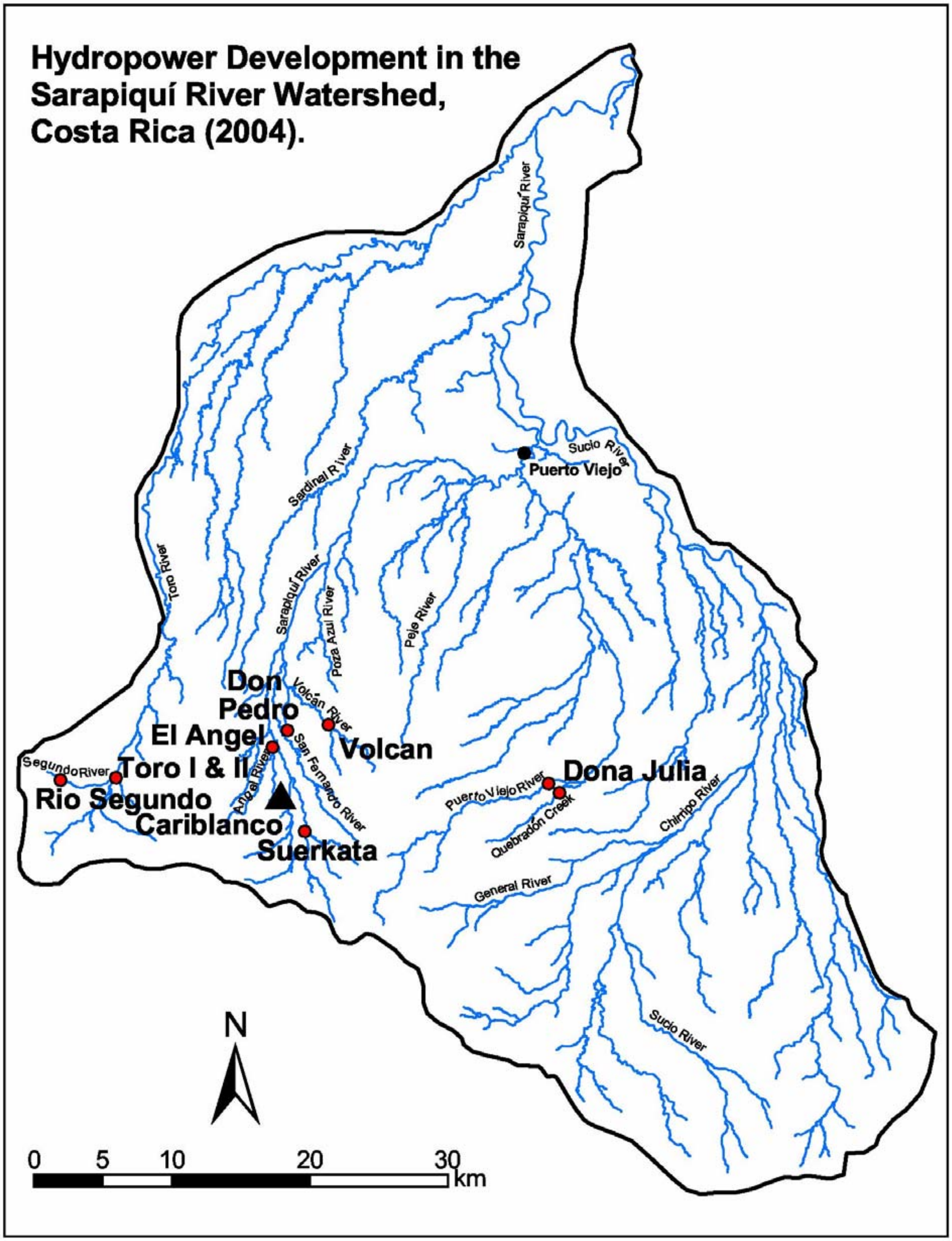


Figure 5.1. Map of Sarapiquí River watershed. Operational hydropower plants are shown with red circles. The location of the Cariblanco Dam, under construction on the Sarapiquí River, is indicated by a black triangle. (Map elaborated by A. Trabucco).

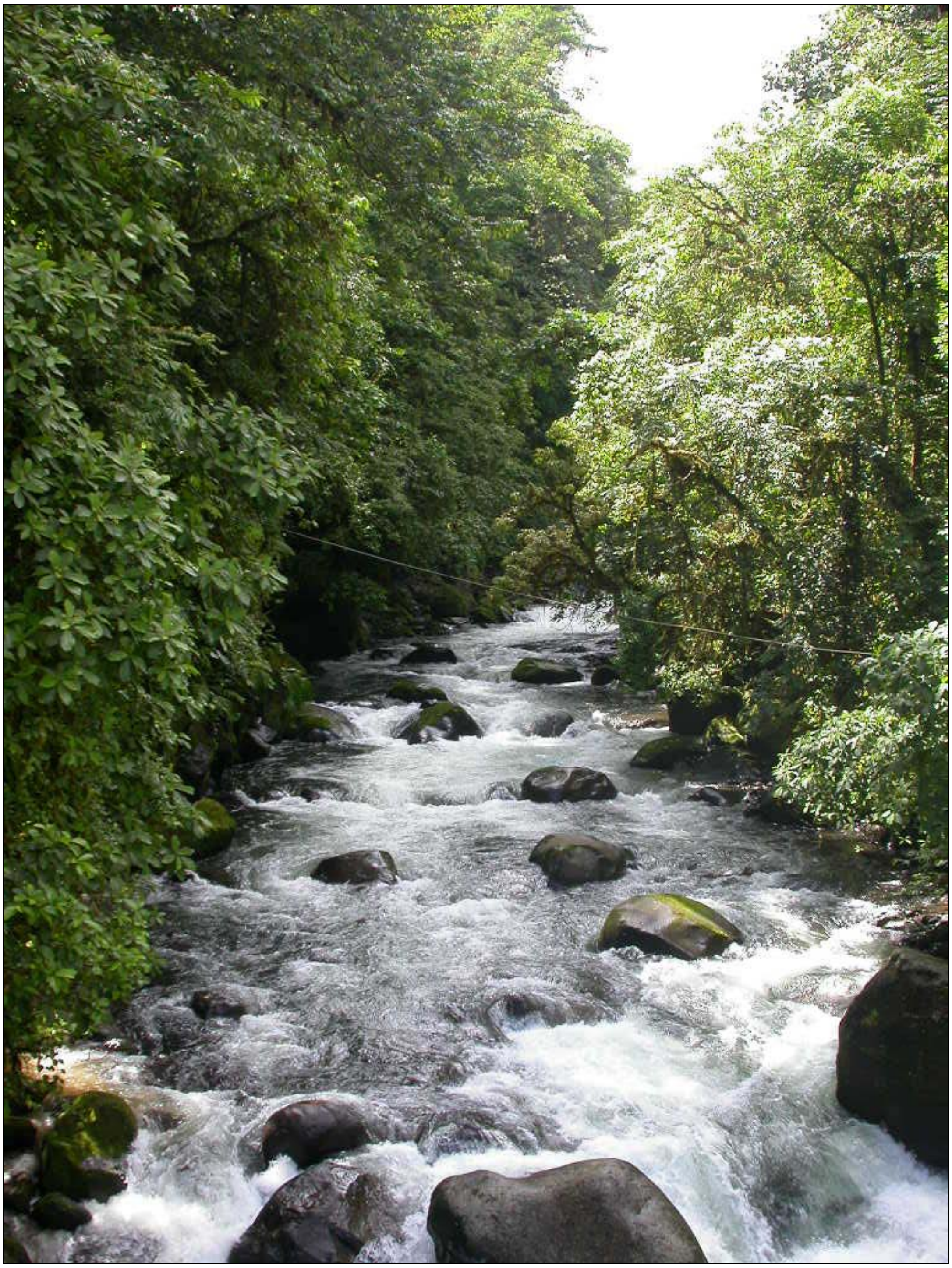


Figure 5.2. Photo of Sarapiquí River near the bridge to the town of Virgen del Socorro. Construction on the Cariblanco Dam began immediately downstream from this site in 2003. Photo by EAO, 2004.

(a)

(b)

Figure 5.3. Cattle pastures (a) and pineapple plantations (b) are among the principal agricultural land uses in Sarapiquí, Costa Rica. Photo by EAO, 2004.

Figure 5.4. Banana agriculture in Sarapiquí, Costa Rica. Large, commercial plantations cover more than 15,000 hectares of land in the area. Photos taken near Finca Zurqui, Puerto Viejo de Sarapiquí; by EAO, March 2004.

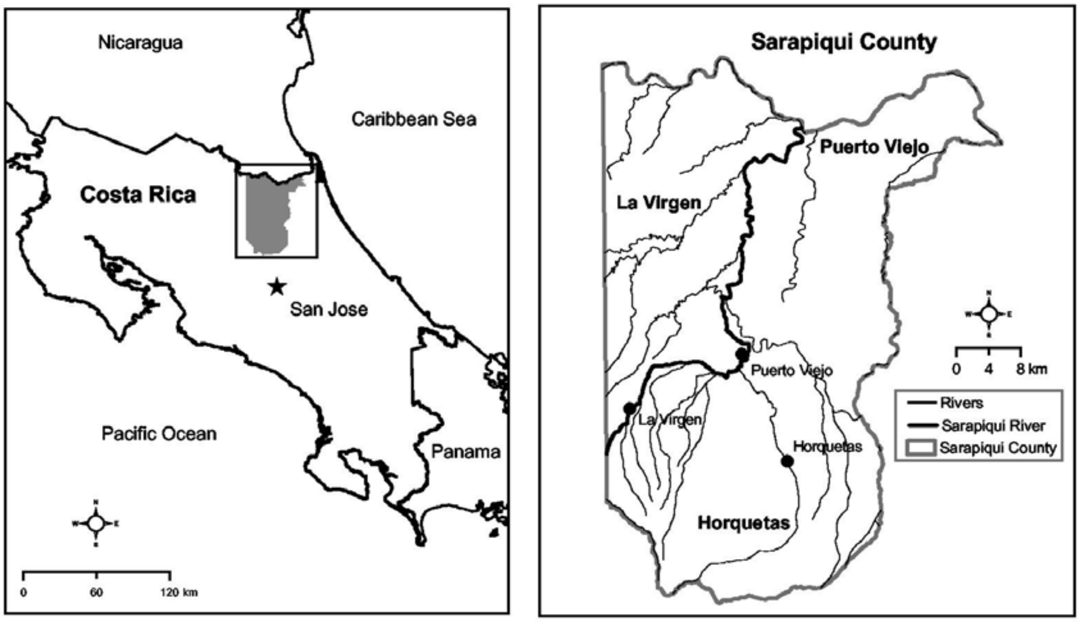


Figure 5.5. Map of Sarapiquí County, Costa Rica. Sarapiquí County comprises three districts: La Virgen, Horquetas, and Puerto Viejo and has a population of about 45,000 inhabitants, according to a 2000 census. The location of the principal town of each district is also shown on the map with a circle and all towns are located along rivers. These towns share the name with the district in which they are located. The Sarapiquí River, shown in bold, bisects the county. (Map elaborated by M. Snyder)

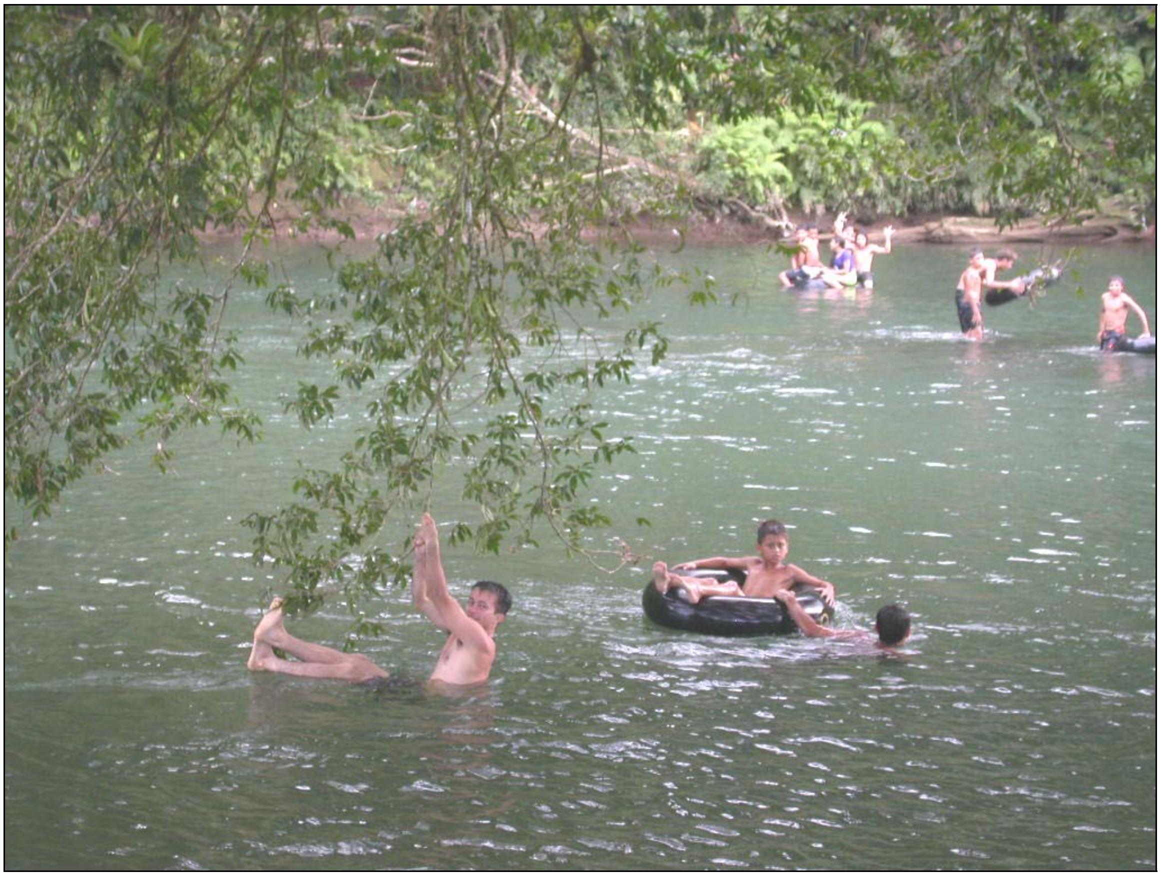


Figure 5.6. The Sarapiquí River is commonly used for swimming and attracts people from all over northeastern Costa Rica on Sundays and holidays. Photo taken in Barrio Cristo Rey, Puerto Viejo de Sarapiquí by EAO, 2004.

Figure 5.7. Boats used for transportation and tourism on the Sarapiquí River downstream from the town of Puerto Viejo. Photo taken by EAO at ‘El Muelle’ in Puerto Viejo, 1999.

Figure 5.8. A sign posted by ABAS along the banks of the Puerto Viejo River near Horquetas, Sarapiquí that gives information about the river and the Sarapiquí watershed. Photo by EAO, 2004.

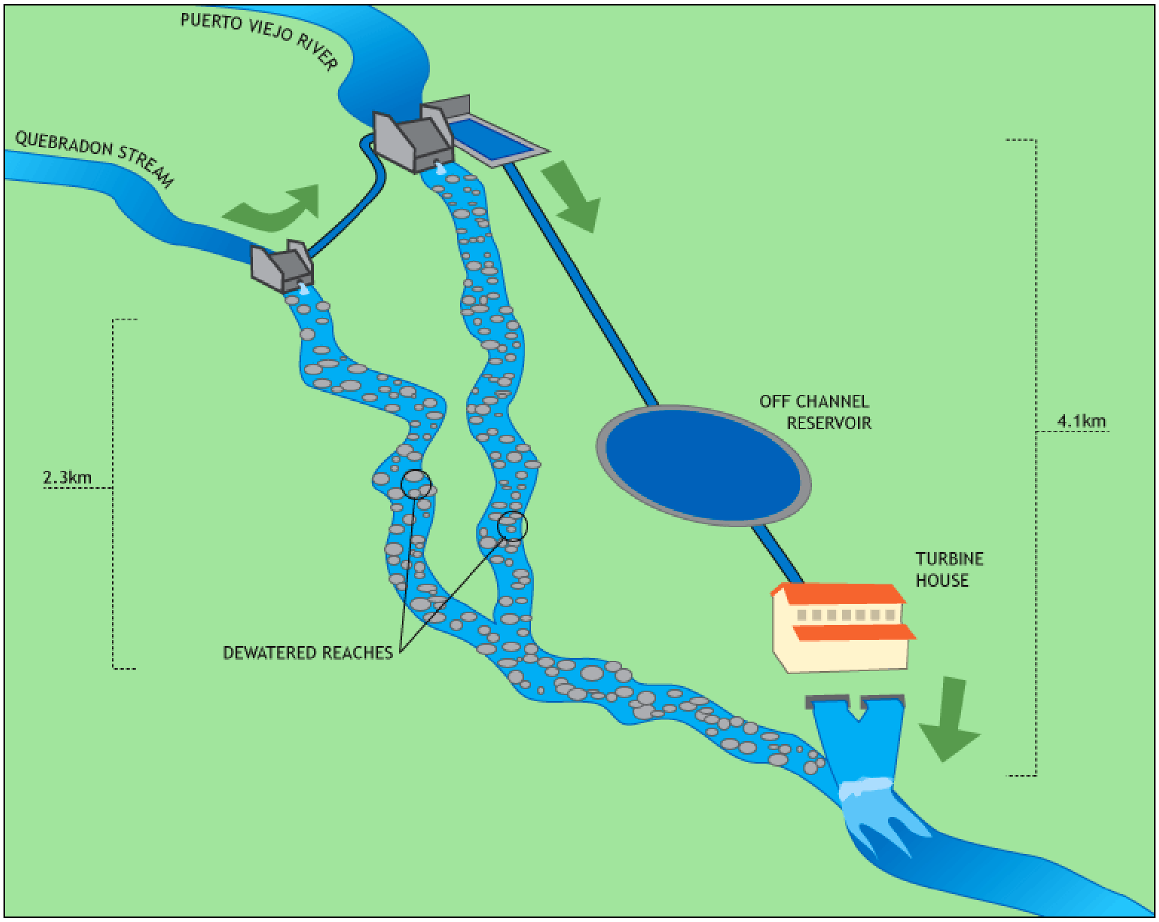


Figure 5.9. Example of diversion dam operations. Water is diverted from the river into a tunnel or pipeline. River water is stored in an off-channel reservoir until peak hours of demand, then run down a gradient to a turbine house. Water is used to generate electricity and then returned to the river. This schematic is based on the Doña Julia Hydroelectric Center that operates on the Puerto Viejo River and the Quebradon stream. (Figure by C. Lowe)

Figure 5.10. One of several signs posted downstream from the Doña Julia Hydroelectric Center on the Puerto Viejo River. Translation: DANGER. Sudden increases in the flow of the river and water level without previous notice. Photo taken by EAO near the bridge crossing the river near Cubujuqui, 2001.

Figure 5.11. Signs around the town of Puerto Viejo de Sarapiquí that urge opposition to the proposed La Virgen Hydropower Project. 'No a la Represa' means 'say no to the dam' in English. Photos by EAO, 1999.

AMIGOS SARAPIQUEÑOS

COMO USTEDES SABEN EL RIO SARAPIQUI REPRESENTA UNA GRAN IMPORTANCIA HISTORICA PARA NUESTRO CANTON. ES UNO DE LOS PRINCIPALES RECURSOS NATURALES, ASI COMO PARTE MUY IMPORTANTE EN NUESTRA ECONOMIA. MIENTRAS NOSOTROS LUCHAMOS PARA CONSERVARLO Y HACERLO CADA DIA MAS ATRACTIVO, HAY GRANDES INTERESES DE COMPAÑIAS MULTINACIONALES PARA DESTRUIRLO.

ESTAN PLANIFICADOS 19 PROYECTOS HIDROELECTRICOS, LO CUAL TERMINARIA CON FLORA Y FAUNA, MANTOS ACUIFEROS Y SU HISTORIA EN GENERAL.

NO PERMITAMOS QUE ESTO OCURRA. ACUDA ESTE PROXIMO VIERNES 6 DE MARZO A LAS 3 DE LA TARDE A LA MUNICIPALIDAD.

!!JUNTOS DEFENDAMOS AL CANTON DE SARAPIQUI!!

!!DEFENDAMOS HOY PARA NO LAMENTAR MAÑANA!!

POR COMITE AMIGOS DE SARAPIQUI

WILLIAM ROJAS UGALDE
CED 2-290-490

Figure 5.12. Flyer posted around the town of Puerto Viejo de Sarapiquí in 1999 informing local residents of hydropower development in the watershed and urging them to oppose further dam construction.

EL PLEBISCITO DEL RIO SARAPIQUI ESTA PENDIENTE

COMUNICADO A LOS CIUDADANOS SARAPIQUEÑOS

1- Aunque el Plebiscito convocado por la Municipalidad y solicitado por el pueblo se ha atrasado, este permanece en pie. Ya el Tribunal Supremo de Elecciones entregó el Manual a la Municipalidad de Sarapiquí para que elabore el Reglamento del Plebiscito.

2- El Consejo nombró una Comisión responsable de elaborar todo lo concerniente al Plebiscito, en ella están algunos regidores, el Alcalde y el Asesor legal de la Municipalidad, este último tendrá que elaborar el reglamento para darlo a conocer al Consejo Municipal.

3- Es nuestro deber apresurar a esa Comisión para que tenga listo el Reglamento lo antes posible. A partir de que el Reglamento esté listo El Concejo Municipal convocará con tres meses mínimo de tiempo el Plebiscito, de acuerdo al Manual que entregó el Tribunal Supremo de Elecciones.

4- El pueblo debe tener presente que de acuerdo a todas las interpretaciones legales, lo que decida cualquier Plebiscito es sagrado y si el pueblo decide que no quiere la represa eso es sagrado y se respetará. Por eso es tan importante que se convoque esta votación y por eso son tan importantes los Plebiscitos.

5- Hasta este momento la Empresa que quiere construir la represa de la Virgen, es decir la Empresa de Servicios Públicos de Heredia, no tiene permisos Municipales y no tiene ninguna concesión de aguas.

6- Las organizaciones que nos hemos comprometido en la lucha para salvar al río Sarapiquí y para salvaguardar la seguridad de los sarapiqueños, no hemos dejado ni un momento de vigilar lo que pasa respecto al río, aunque el proceso es lento lo importante es saber que tenemos el respaldo de las comunidades y que somos fieles a sus intereses, no nos cansaremos porque el Plebiscito se atrase, no retrocederemos ni una pulgada en defender el río Sarapiquí.

7- Presione usted a los regidores de su comunidad para que el Plebiscito se haga pronto. Eso es muy importante.

Asociación de Desarrollo Integral de Puerto Viejo, Asociación de Desarrollo de San Julián, Asociación de Desarrollo Integral de Horquetas, Asociación de Desarrollo de Zapote, ABAS, ACECAN, Cámara de Turismo de Sarapiquí, Asociación de Transportistas Acuáticos, Asociación de Productores de Gerika, Asociación Agroindustrial La Esperanza, Asociación de Guías Naturalistas, Asociación de Vigilantes de Sarapiquí, Centro de Enseñanza, etc.

Figure 5.13. Flyer posted around Sarapiquí County in 2000 informing local residents of the *plebescito*, or community voting event.

Figure 5.14. Photo of Sarapiquí River downstream from the confluence of the Sucio River. Banks on both sides of the river are almost completely deforested from this point until the river discharges into the San Juan River. Photo by EAO, 2001.

CHAPTER 6:

GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Summary

The study addresses the consequences of hydropower development at local, watershed, and national scales. Each of the chapters will be made available to dam owners, the ICE, conservationists, and academics in Costa Rica.

Hydropower development has dramatically changed the Sarapiquí River system over the past decade and a half. Its impacts have been both positive and negative. Hydropower projects in Sarapiquí can now provide ~10% of electricity in a country of 4 million people. However, hydropower developments have transformed free-flowing rivers in Sarapiquí into altered systems, both in terms of physical and biological conditions. In addition, the combined impacts of hydropower and other human activities in Sarapiquí are substantial: 10% of stream length in the watershed is now upstream from dams and 31 km of streams have been dewatered. Furthermore, hydropower projects have resulted in increased competition for and conflicts over freshwater resources. Nevertheless, hydropower development has been a catalyst for river conservation in the Sarapiquí region: it has provoked local residents to think critically about the importance of freshwater and has motivated organization of conservation activites in the watershed.

Results presented here provide only a glimpse of the complex ecological and social effects of hydropower development in Sarapiquí. An outcome of this study has been the generation of a new set of ideas that can serve as a base for further research in Sarapiquí and other tropical river systems. In addition, this study has produced a series of recommendations for monitoring and management of rivers in Sarapiquí.

Recommendations for research and management

National scale

Instream flows—At a national scale, more research is needed to determine appropriate instream flow methodology for Costa Rican rivers. Presently, guidelines issued by the MINAE (Ministry of Environment and Energy) recommend that 10% of average annual discharge remain in a river at all times downstream from a dam. However, these guidelines were based on studies from North American and European rivers (R. Corrales, Doña Julia Hydroelectric Company, personal communication) and may or may not be ecologically applicable to tropical systems, which are characterized by larger and more frequent flooding events and seasonality in precipitation. Moreover, instream flows are still only 'recommended' in Costa Rica; legislation is needed to mandate their use. The recent organization of workshops (2/04; 3/04) and ongoing research being conducted by the ICE are steps in the right direction (R. Rojas, ICE, personal communication).

Managing electricity demand—The demand for electricity in Costa Rica is growing by approximately 6% annually. The country should explore ways to manage or curb these increases in demand. Demand-side management programs have been shown to be effective in other parts of the world and may be useful in Costa Rica as well. Also, campaigns to educate the public on wise use of electricity (and TV advertisements, with basic recommendations about turning off lights and appliances when not in use) may help to decrease pressure on electricity resources.

Exploring alternative generation scenarios—A major component of sustainable development of electricity resources is the exploration of alternative sources of electricity. In Costa Rica, wind and solar energy are promising sources, based on the climate of the northern Pacific slope, which is characterized by dry, windy weather from roughly December to July. Currently, wind and solar plants account for <5% of electricity; Costa Rica should try to expand the relative contributions of these sources in the future. One potential option that the country could explore is the adoption of a 'shifting dependence' system, where the contributions of hydropower and wind / solar vary throughout the year. For example, during very wet months (June-December), small hydropower on the Caribbean slope could be used as a primary source of electricity for the country, since our results suggest that the ecological effects of diversion dams may be lessened during wetter periods. Dry months (January-May) are characterized by hot sun and windy weather on the northern Pacific slope, and wind / solar could be used as a primary source of electricity at this time.

Watershed scale

Cumulative effects assessment—More research is needed on cumulative effects of hydropower and other human activities on watersheds in Costa Rica. Chapter 3 of this dissertation shows that cumulative effects assessment is possible even when little data is available. Appropriate methods for investigating cumulative effects of human activities should be developed for Costa Rica. These methods should be based on climate, types of human activities, and available data. In the future, cumulative effects assessment should be an integral part of watershed management and environmental impact assessment of individual projects.

Comprehensive biotic surveys—Data on species abundance and distribution of fishes and other aquatic biota do not exist for many rivers in Costa Rica. Where they do exist, data are often outdated, as they were collected 40-50 years ago when a much larger percentage of Costa Rica was forested. Comprehensive surveys of aquatic biota are needed for rivers in Costa Rica, especially those targeted for development. Also, more research on the life history of migratory and sensitive species, especially *Joturus pichardi*, *Agonostomus monticola*, native Cichlid fishes, *Atya spp*., and *Macrobrachium spp*., will be useful for conservation and management purposes.

Discharge monitoring—Currently, there are a limited number of rivers in Costa Rica with discharge monitoring stations. In light of the importance of freshwater resources, more gauges should be installed to collect long-term data and monitor changes in hydrology as a result of rapid hydropower development. Long-term hydrologic data will be useful in the development of instream flow methodologies and in natural history studies of aquatic biota.

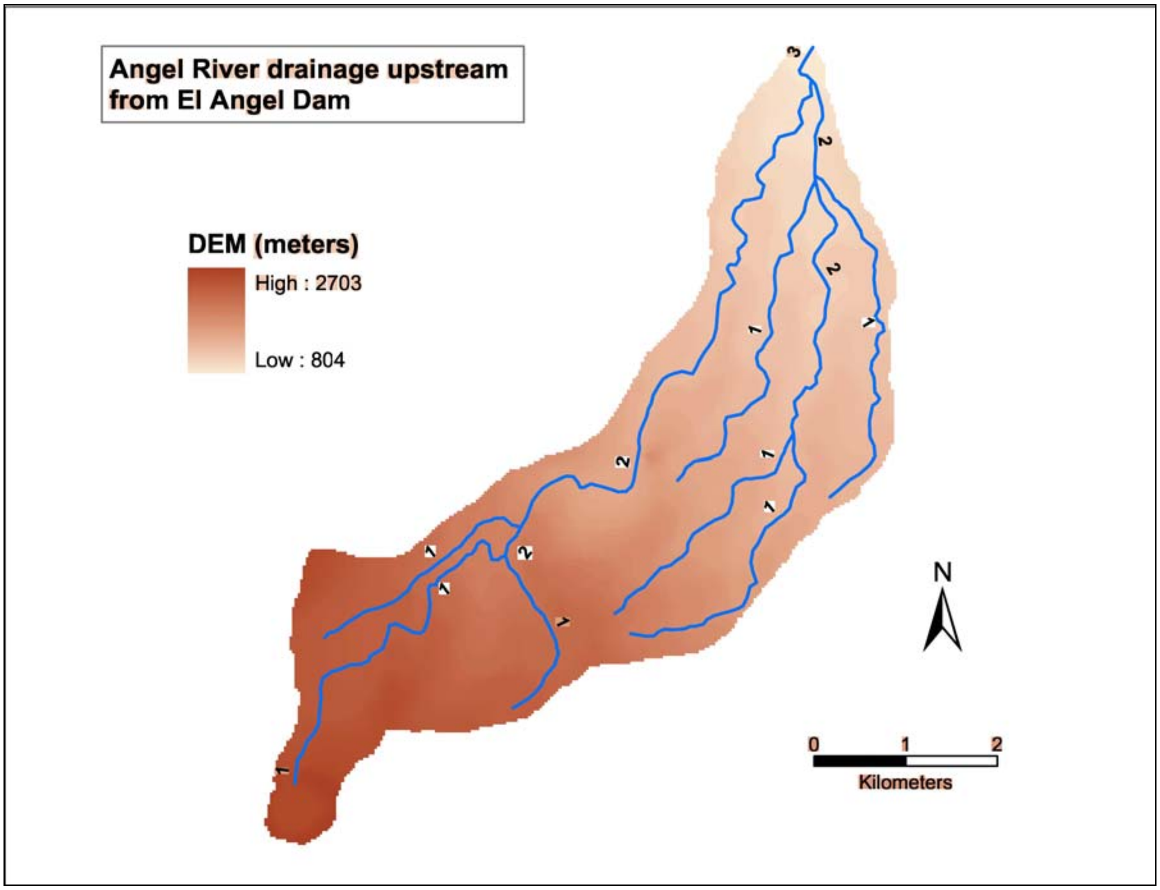
Local scale

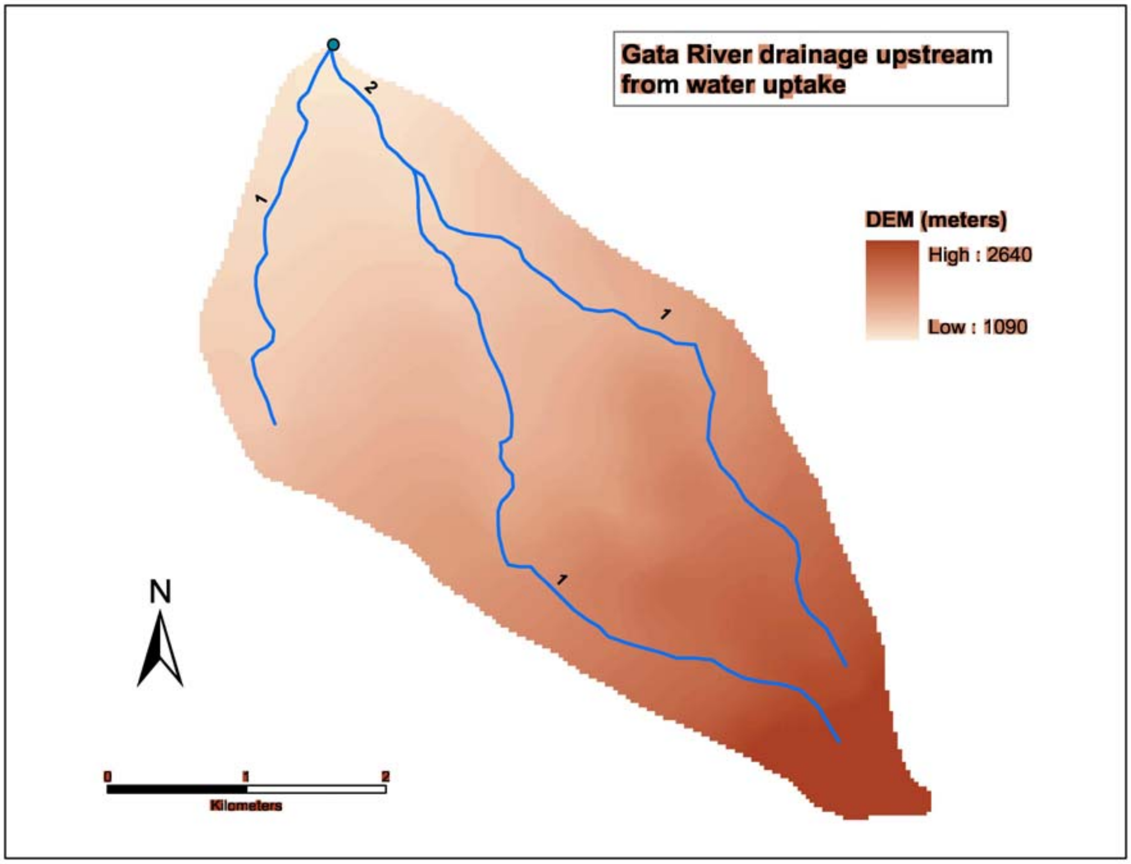
Funded scientific research on dams—Hydropower companies should be required to promote and fund scientific research related to the ecological and social effects of dams. When private hydropower companies apply for a generation contract, a research program should be required in order to obtain the contract. This model has been used with dams in French Guyana on the Sinnamary River (see Ponton et al. 2000). Examples of research needed on dams in Costa Rica include studies of biotic response to hydrologic alterations, population ecology studies upstream from dams that hinder movement of organisms, and geomorphologic studies of channel response to damming.

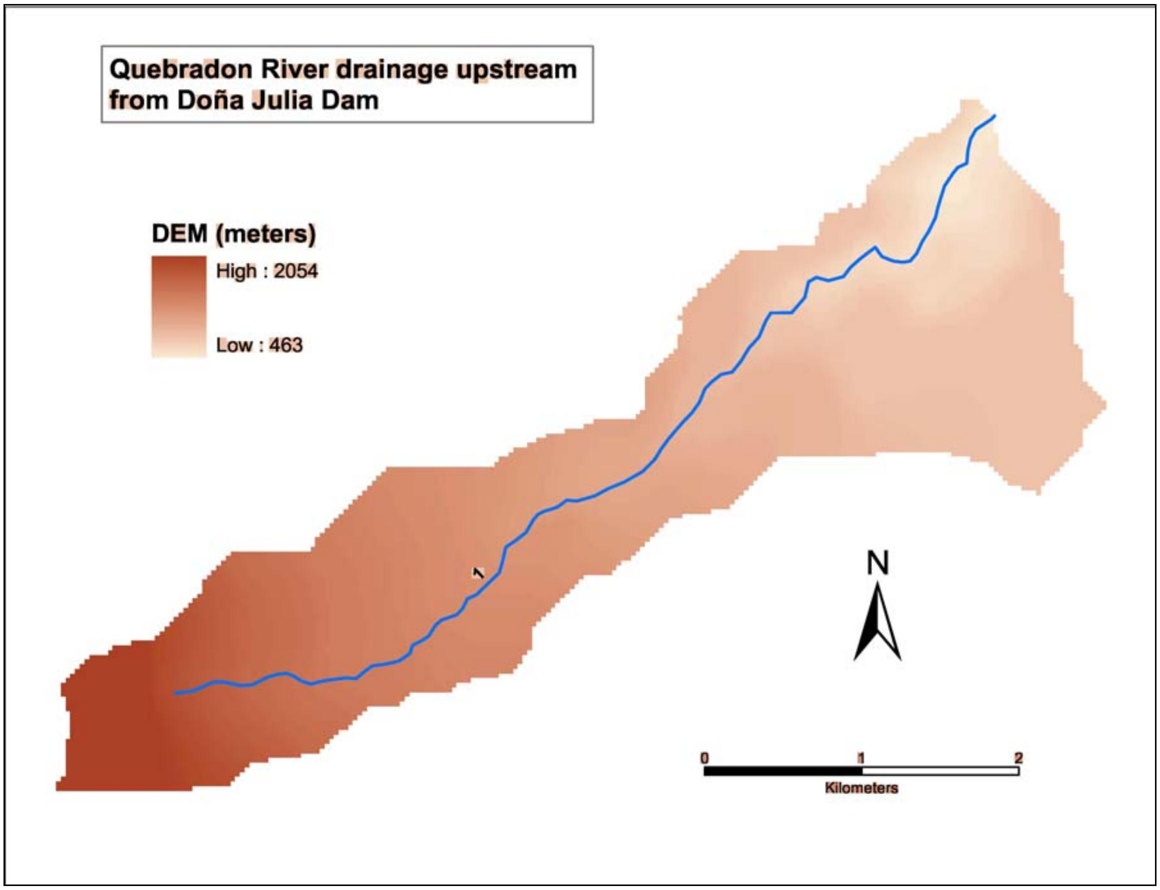
Follow up studies of environmental impacts—A substantial problem with environmental impact assessments in Costa Rica, and worldwide, is the lack of follow up studies. Little to no data are available on the actual impacts of most hydropower projects. Establishment of monitoring programs at specific time intervals is a necessary part of sound impact assessment studies.

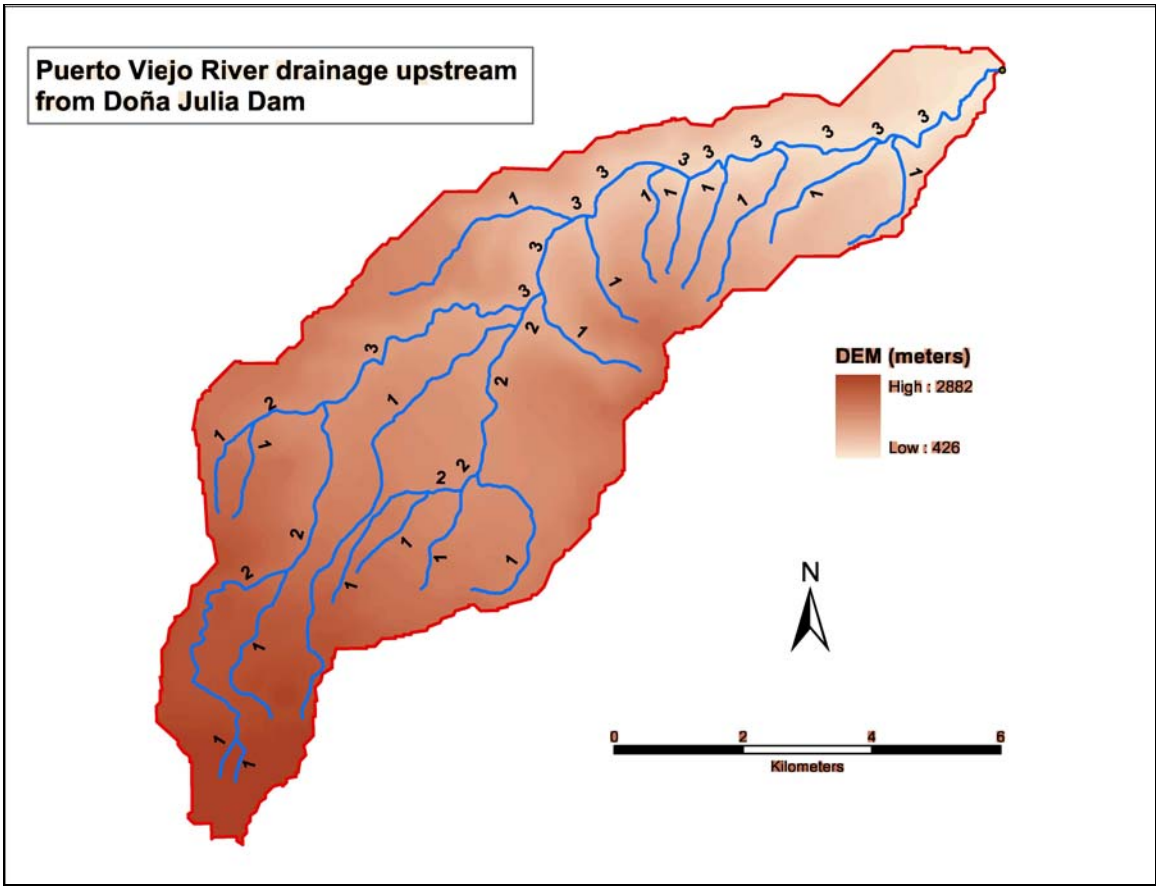
APPENDIX 1:

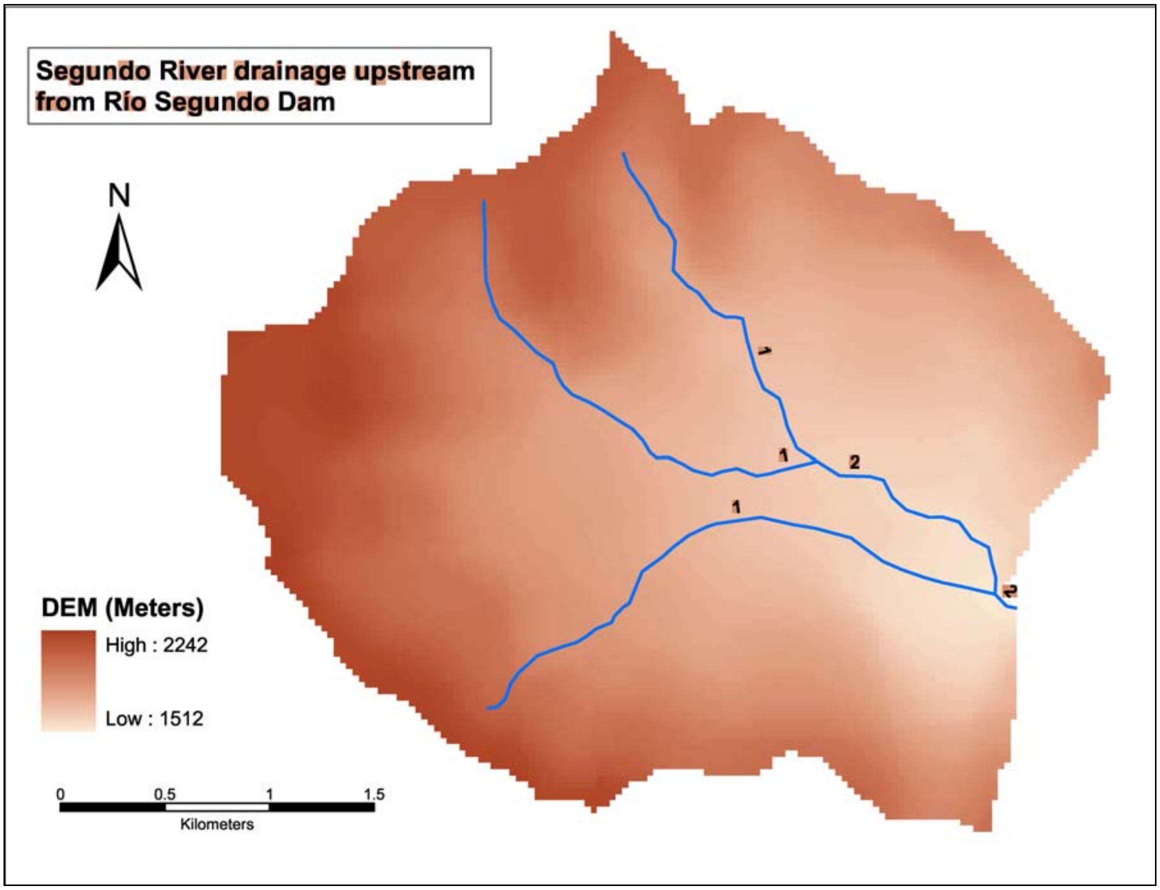
STRAHLER ORDINATION OF DAMMED SUB-BASINS OF THE SARAPIQUÍ RIVER WATERSHED

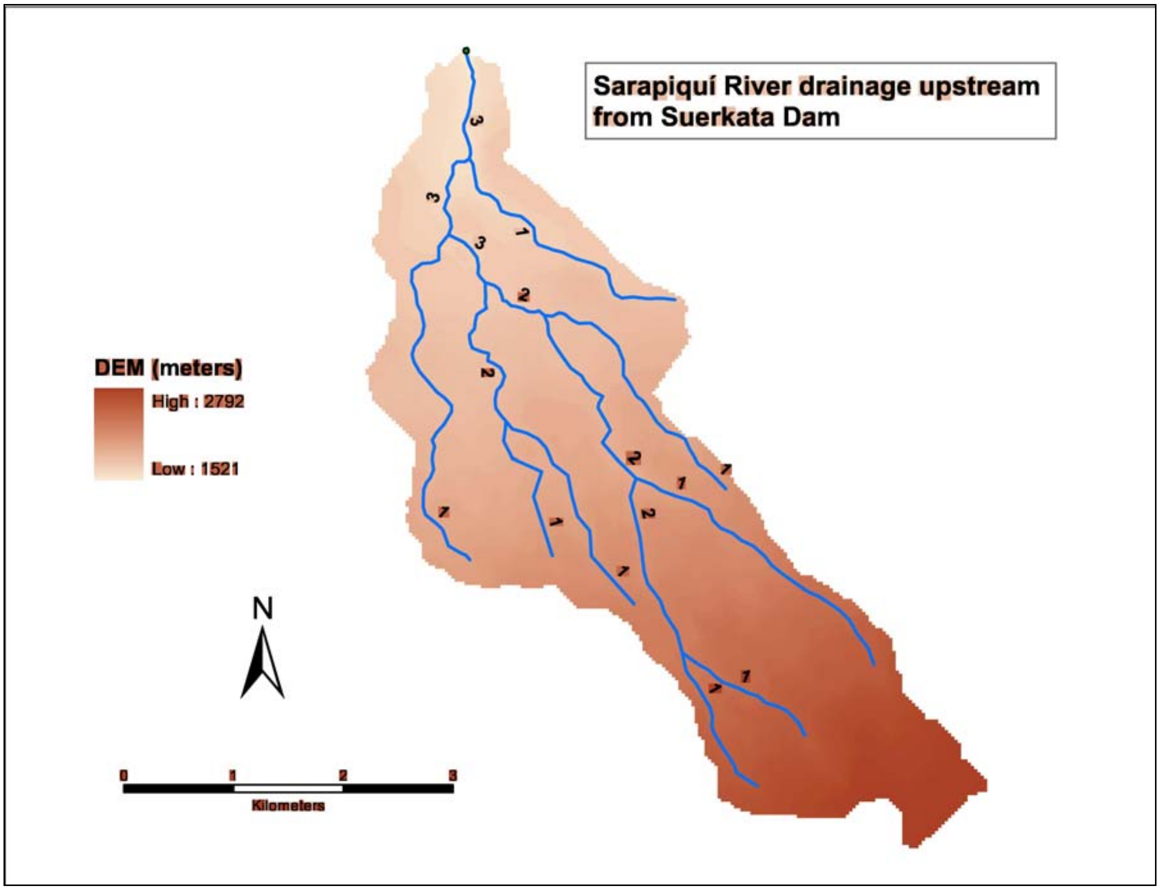

Angel River drainage upstream from El Angel Dam
DEM (meters)
High : 2703
Low : 804
N
0
1
2
Kilometers

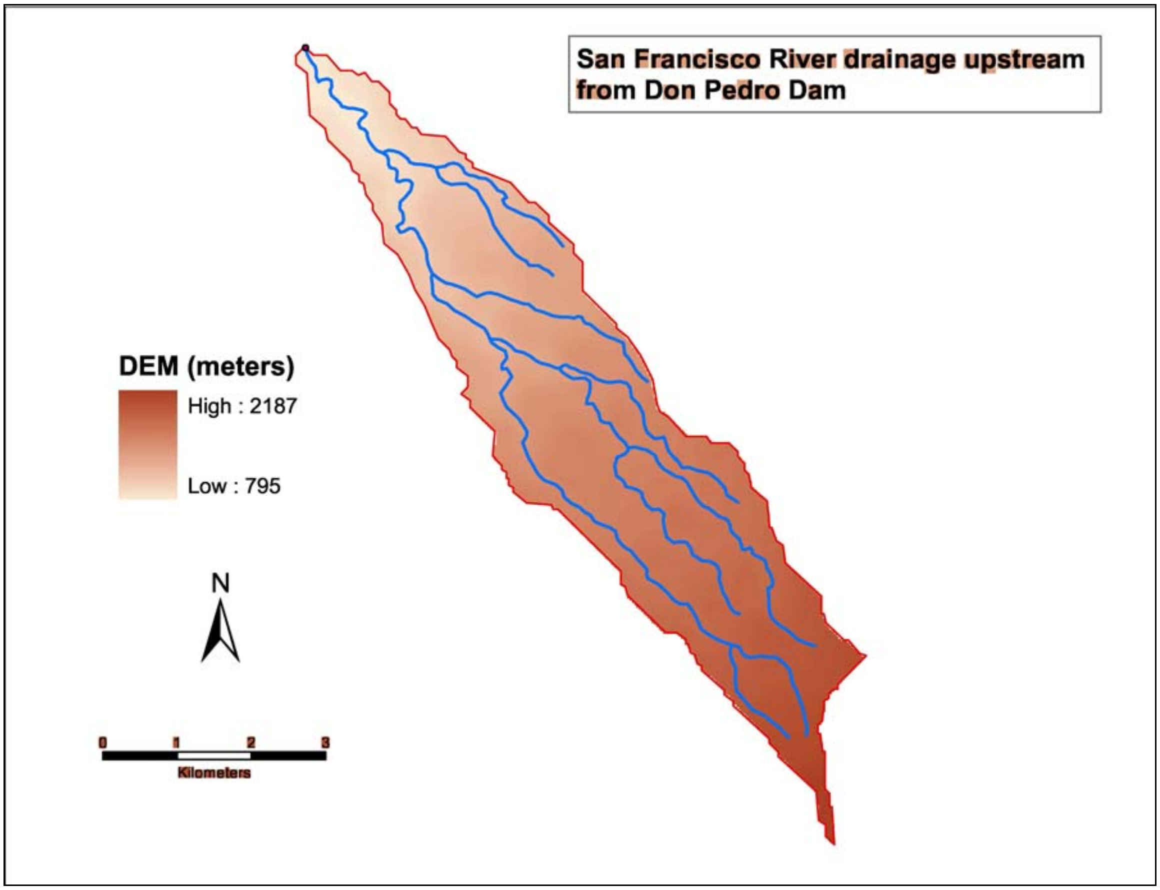

Gata River drainage upstream from water uptake
DEM (meters)
High : 2640
Low : 1090
N
0
1
2
Kilometers
1
2
1
1

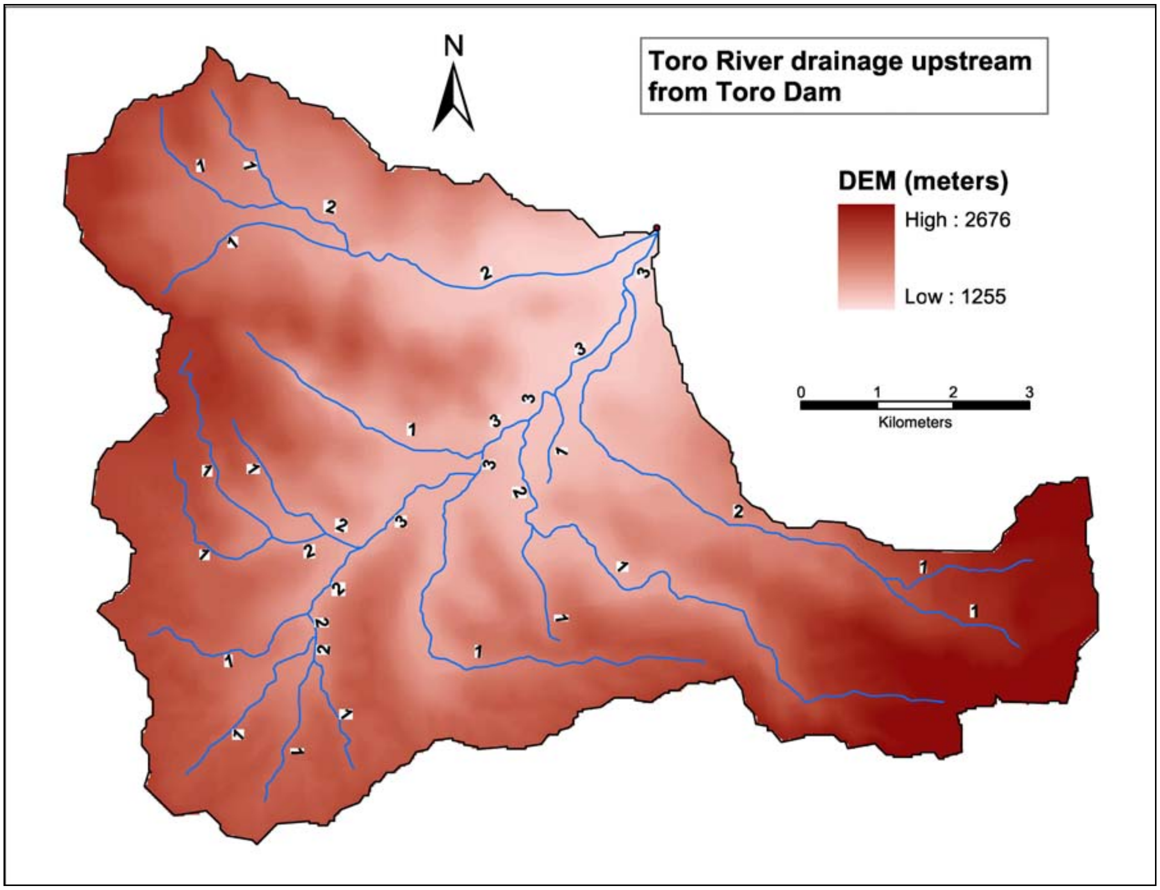

Quebradon River drainage upstream
from Doña Julia Dam
DEM (meters)
High : 2054
Low : 463
N
0
1
2
Kilometers

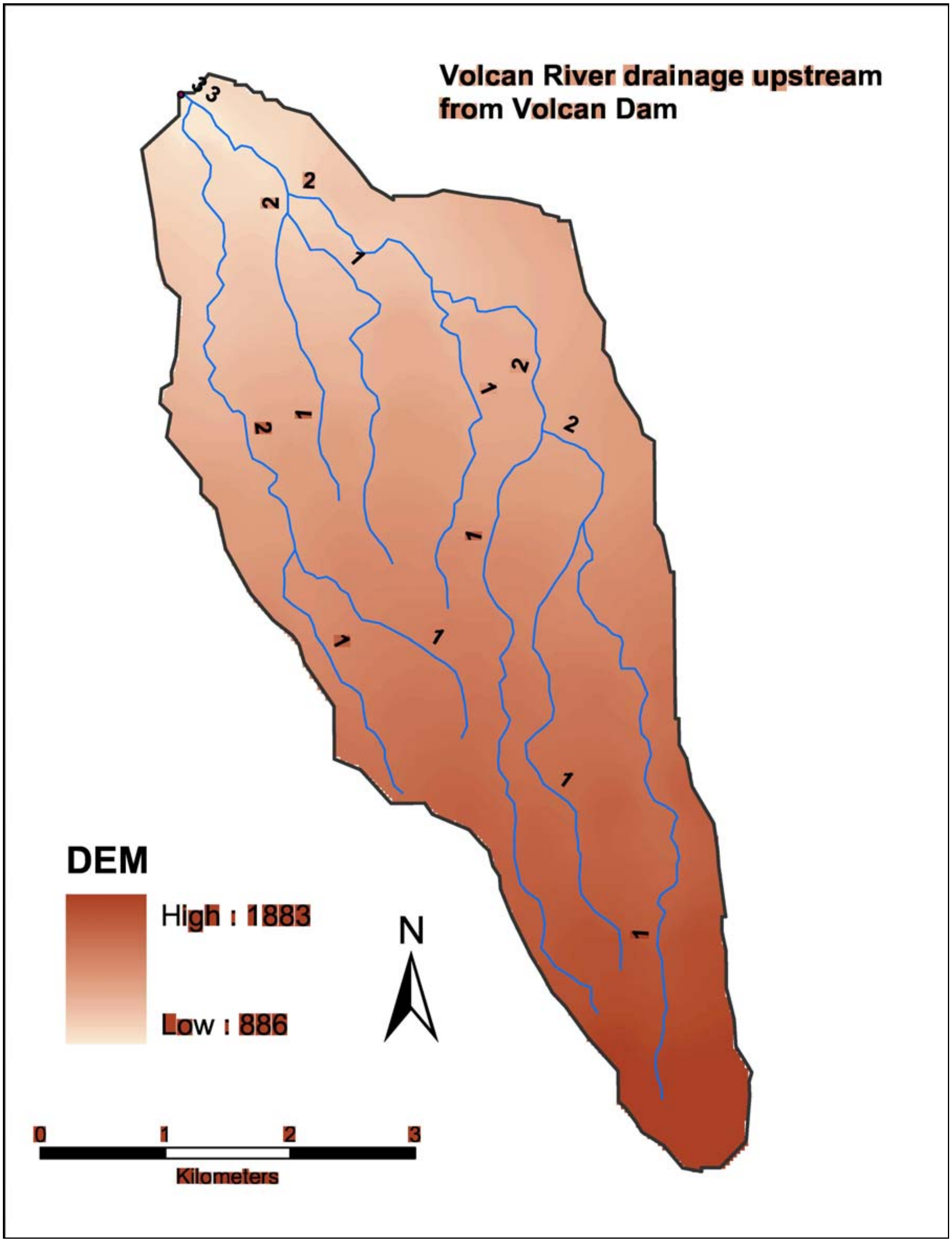

Puerto Viejo River drainage upstream
from Doña Julia Dam
DEM (meters)
High : 2882
Low : 426
N
0
2
4
6
Kilometers


Segundo River drainage upstream from Río Segundo Dam
N
1
1
2
1
2
DEM (Meters)
High : 2242
Low : 1512
0
0.5
1
1.5
Kilometers


Sarapiquí River drainage upstream from Suerkata Dam
DEM (meters)
High : 2792
Low : 1521
N
0
1
2
3
Kilometers

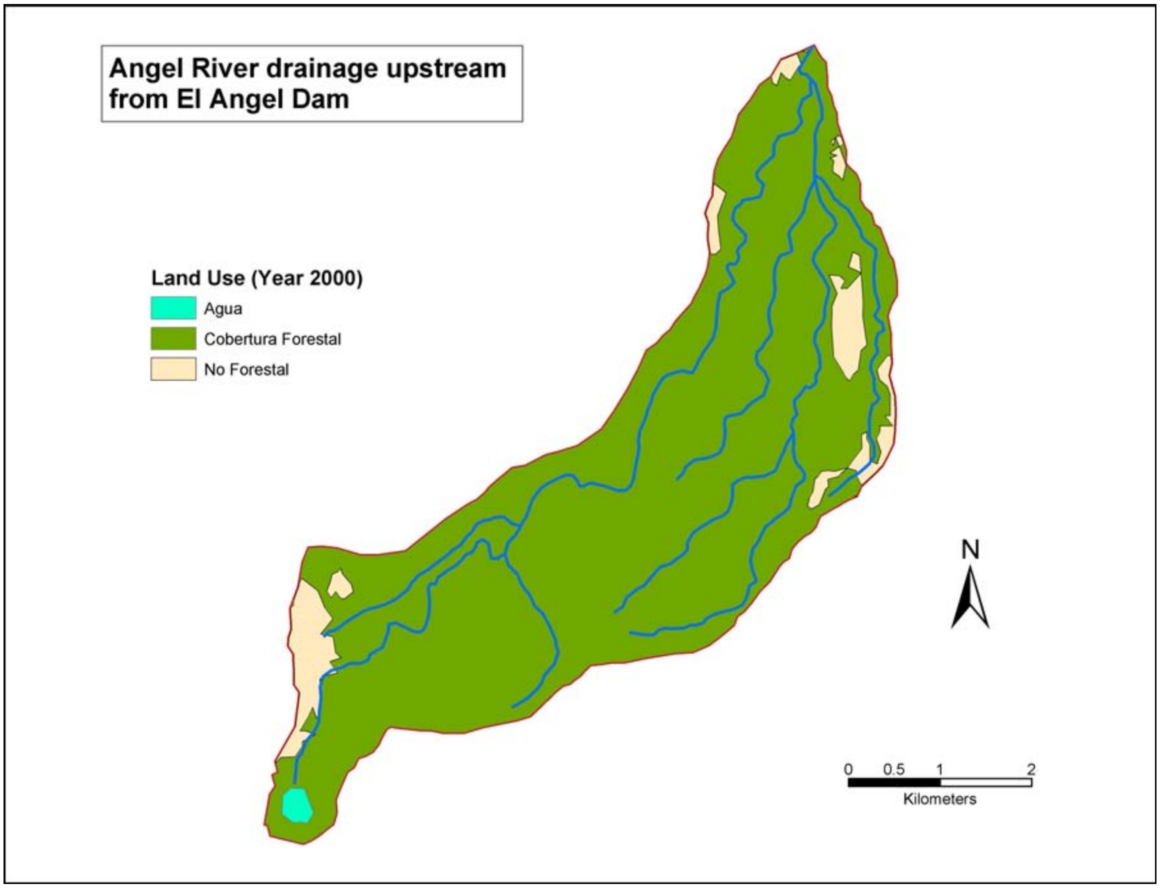

San Francisco River drainage upstream from Don Pedro Dam
DEM (meters)
High : 2187
Low : 795
N
0
1
2
3
Kilometers

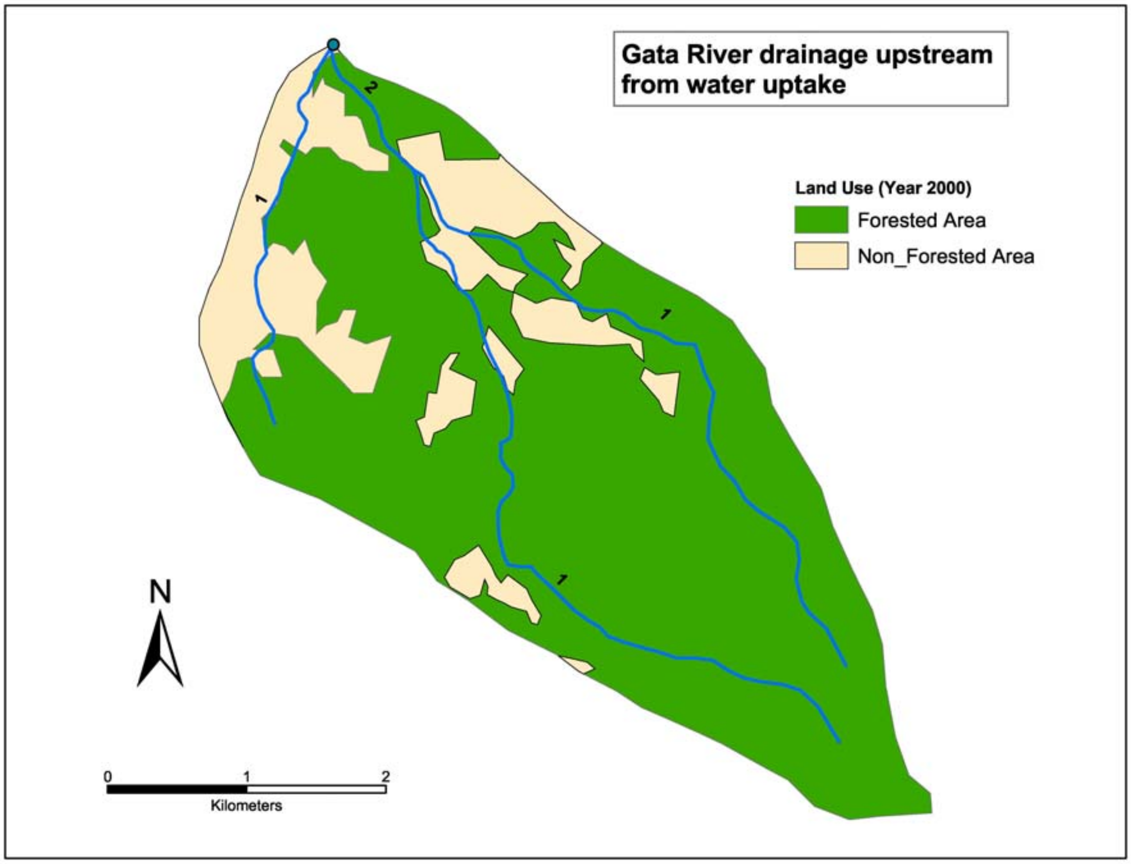

Toro River drainage upstream from Toro Dam
N
DEM (meters)
High : 2676
Low : 1255
0
1
2
3
Kilometers

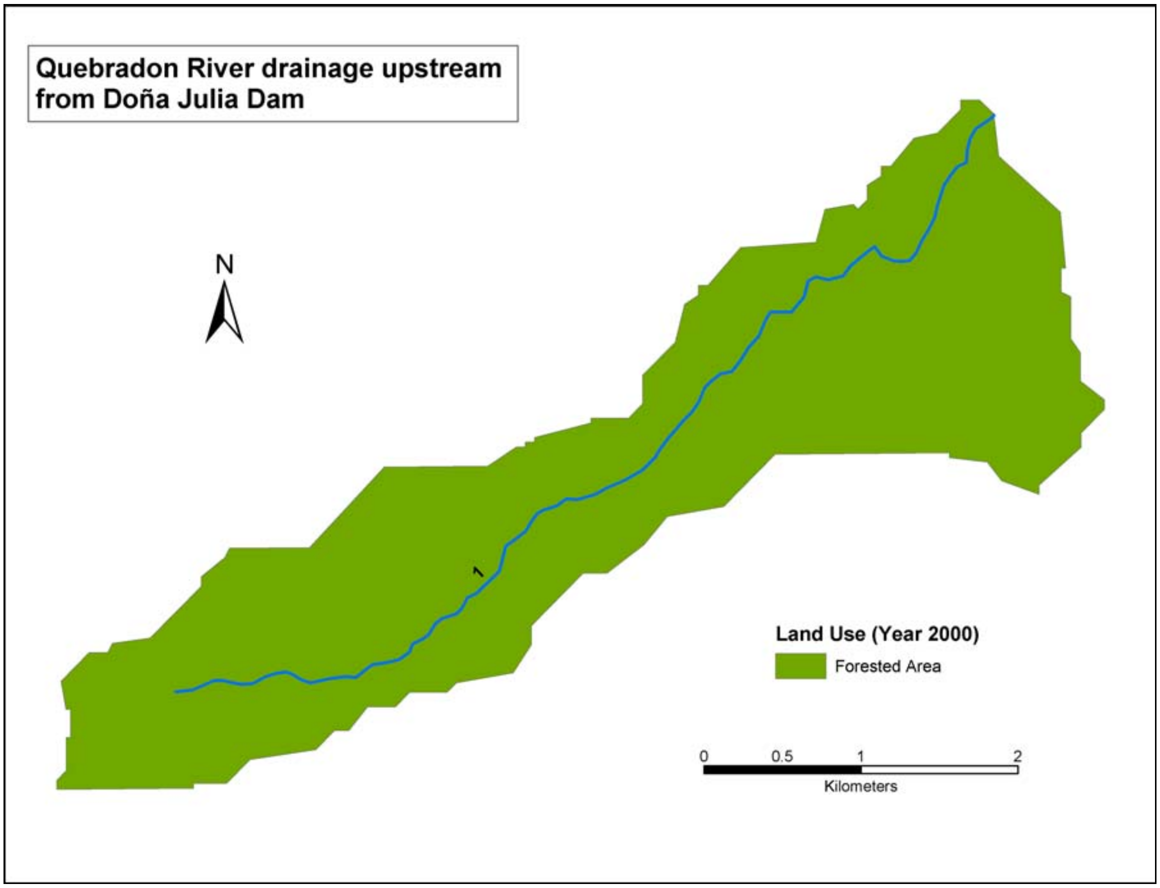

Volcan River drainage upstream
from Volcan Dam
DEM
High : 1883
Low : 886
N
0
1
2
3
Kilometers

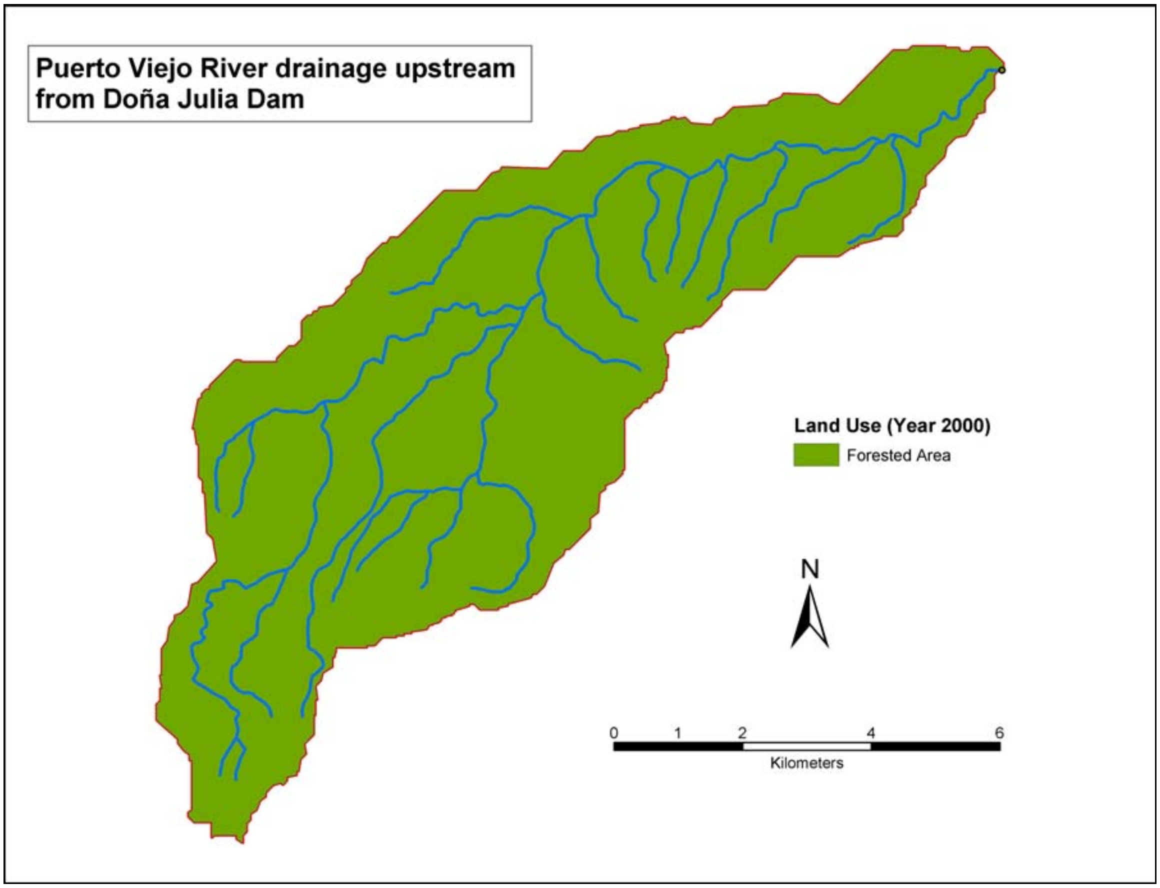
APPENDIX 2

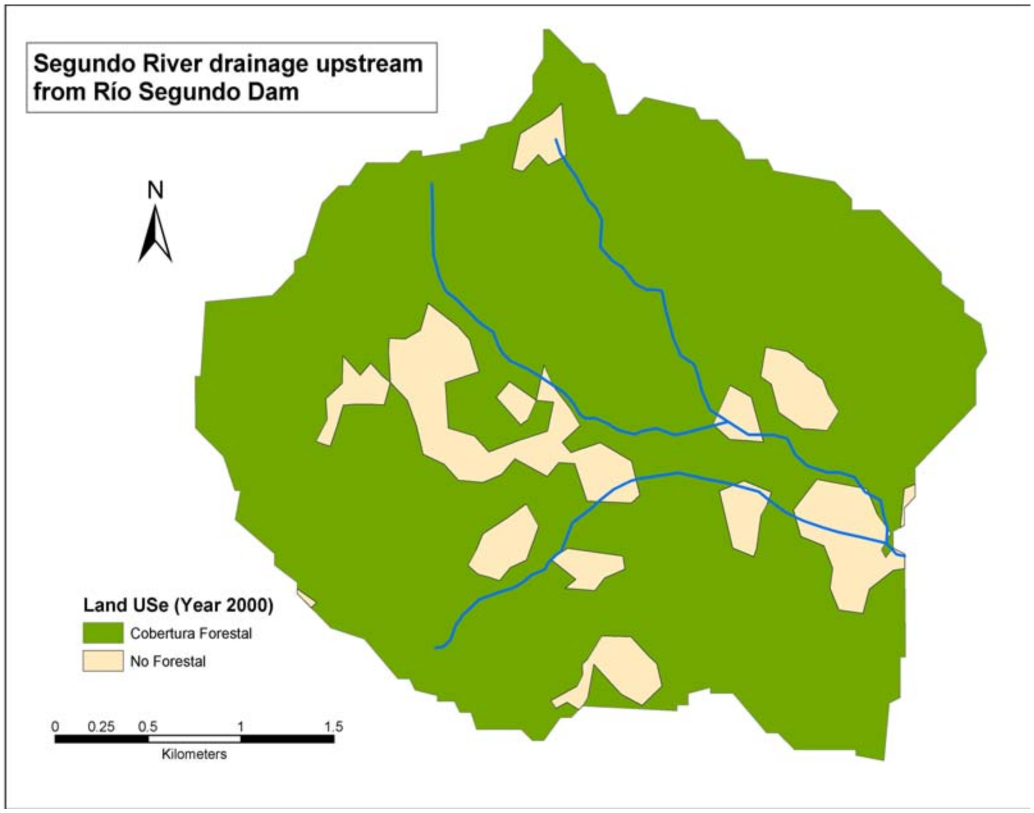
LAND COVER IN DAMMED SUB-BASINS OF THE SARAPIQUÍ WATERSHED


Angel River drainage upstream
from El Angel Dam
Land Use (Year 2000)
Agua
Cobertura Forestal
No Forestal
N
0 0.5 1 2
Kilometers

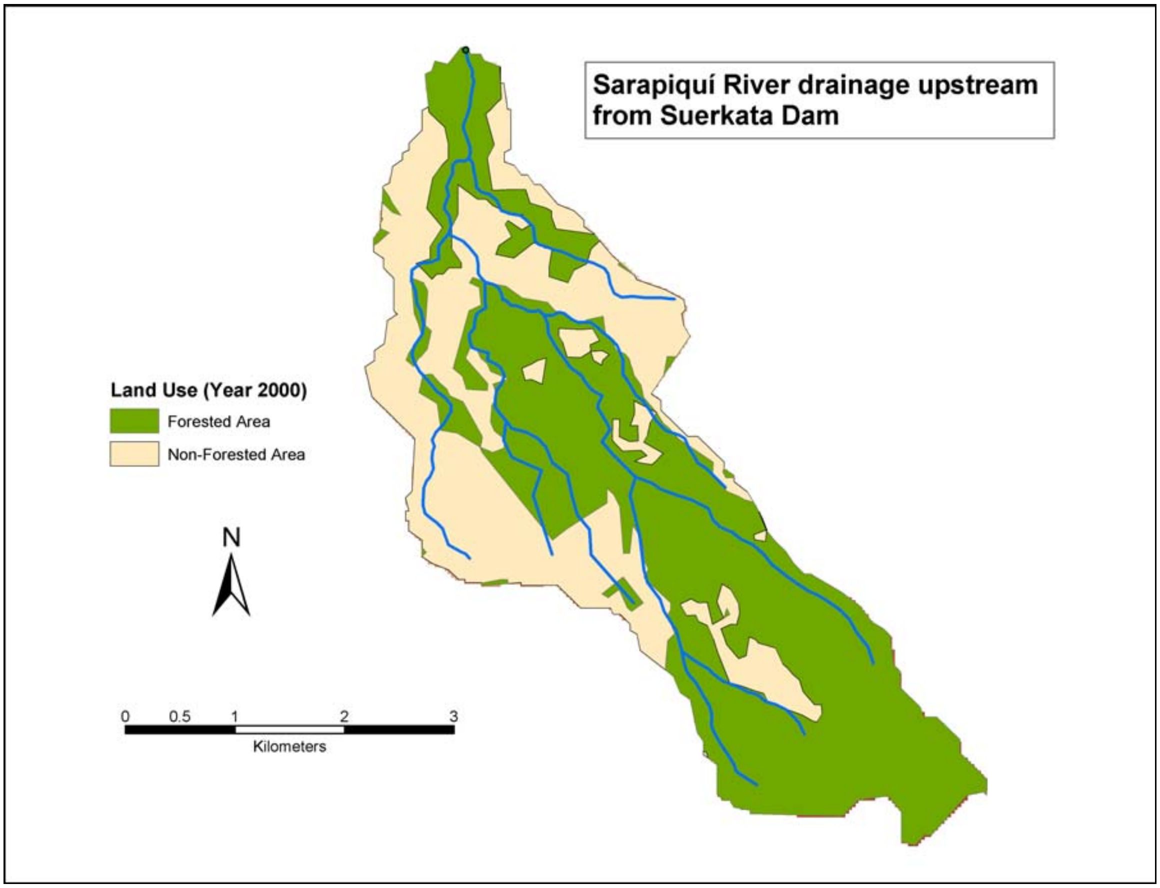

Gata River drainage upstream from water uptake
Land Use (Year 2000)
Forested Area
Non_Forested Area
N
0
1
2
Kilometers
1
2
1
1

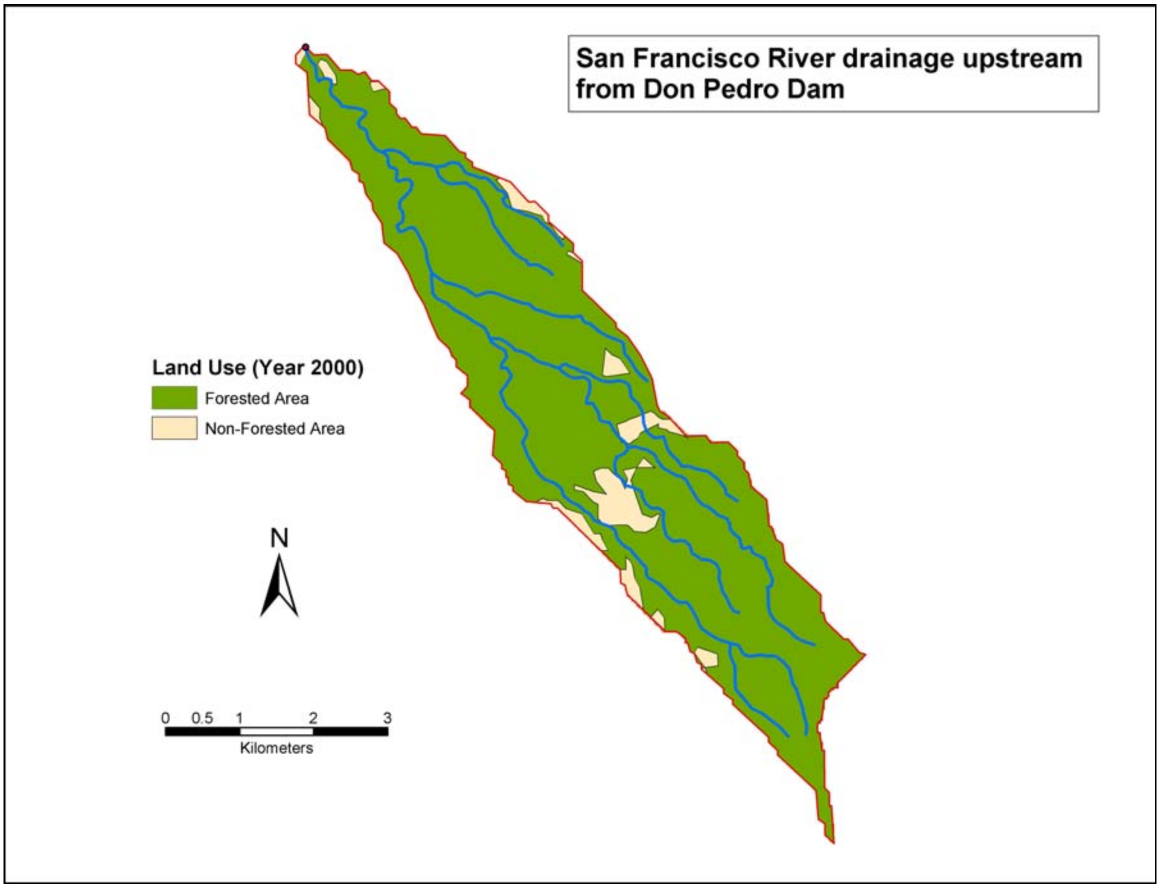

Quebradon River drainage upstream from Doña Julia Dam
N
1
Land Use (Year 2000)
Forested Area
0
0.5
1
2
Kilometers

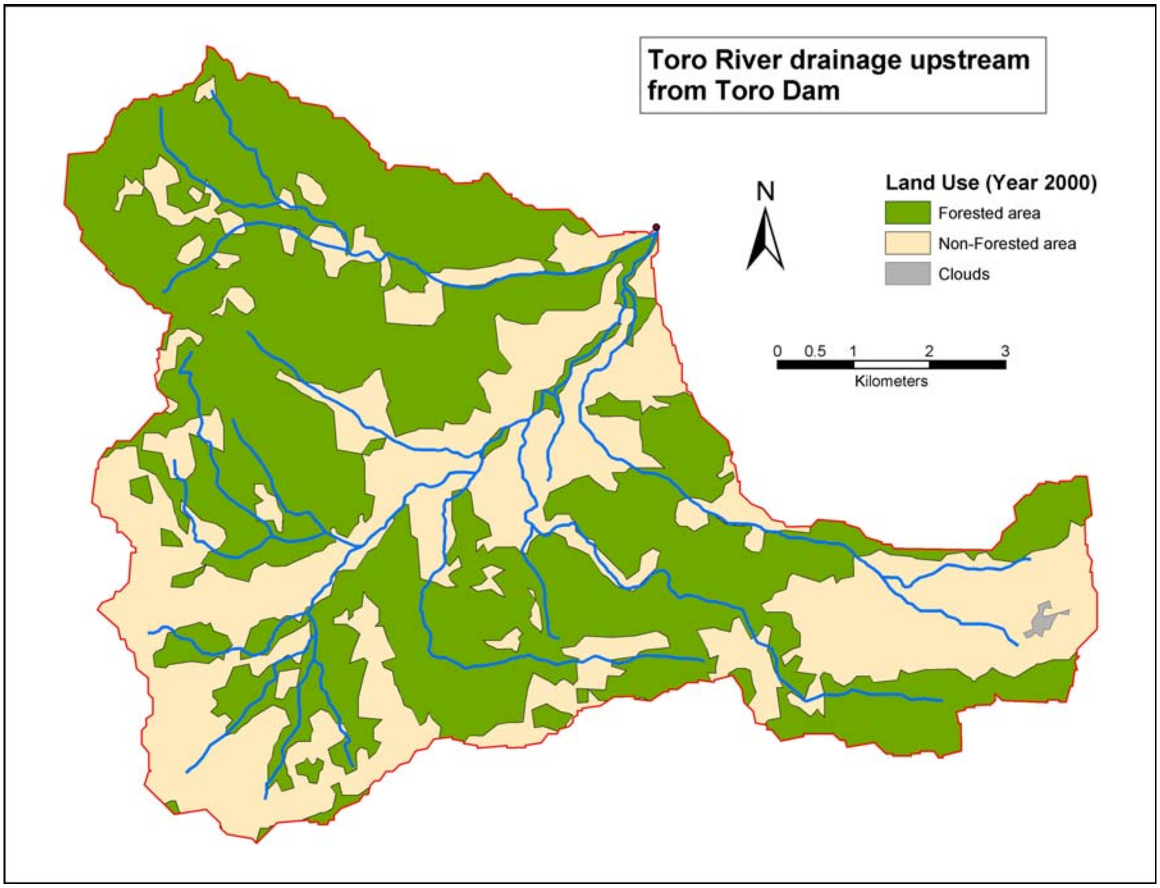

Puerto Viejo River drainage upstream from Doña Julia Dam
Land Use (Year 2000)
Forested Area
N
0
1
2
4
6
Kilometers

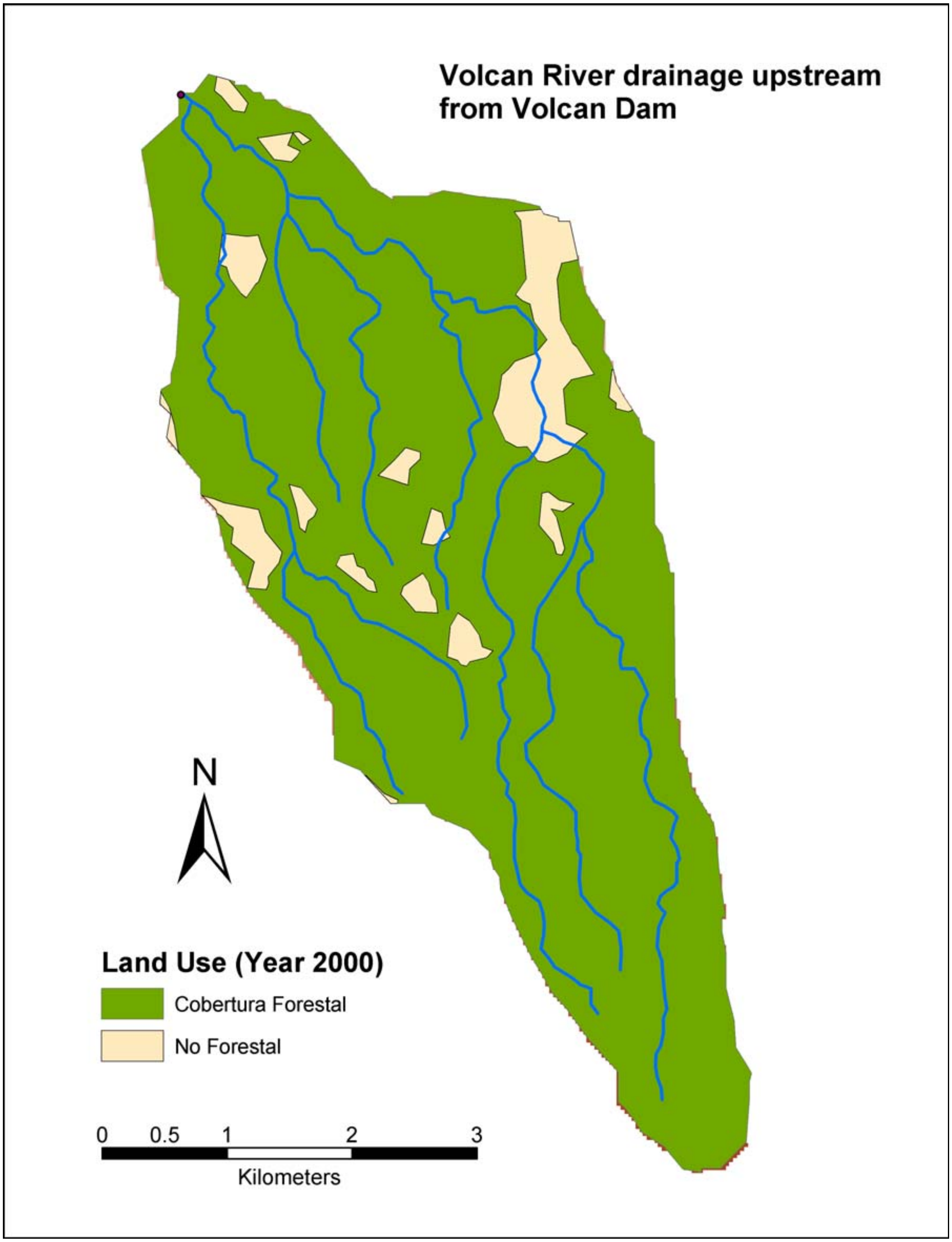


Segundo River drainage upstream
from Río Segundo Dam
N
Land USe (Year 2000)
Cobertura Forestal
No Forestal
0
0.25
0.5
1
1.5
Kilometers


Sarapiquí River drainage upstream from Suerkata Dam
Land Use (Year 2000)
Forested Area
Non-Forested Area
N
0 0.5 1 2 3
Kilometers


San Francisco River drainage upstream from Don Pedro Dam
Land Use (Year 2000)
Forested Area
Non-Forested Area
N
0 0.5 1 2 3
Kilometers


Toro River drainage upstream
from Toro Dam
N
Land Use (Year 2000)
Forested area
Non-Forested area
Clouds
0 0.5 1 2 3
Kilometers


Volcan River drainage upstream
from Volcan Dam
N
Land Use (Year 2000)
Cobertura Forestal
No Forestal
0
0.5
1
2
3
Kilometers