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Quantifying the extent of river fragmentation by hydropower dams in the Sarapiquí River Basin, Costa Rica[†]

ELIZABETH P. ANDERSON[a,*], CATHERINE M. PRINGLE[a] and MARY C. FREEMAN[b]

[a] *Institute of Ecology, University of Georgia, Athens, GA 30602, USA*

[b] *United States Geological Survey, Patuxent Wildlife Research Center, Athens, GA 30602, USA*

ABSTRACT

1. Costa Rica has recently experienced a rapid proliferation of dams for hydropower on rivers draining its northern Caribbean slope. In the Sarapiquí River Basin, eight hydropower plants were built between 1990 and 1999 and more projects are either under construction or proposed. The majority of these dams are small (<15 m tall) and operate as water diversion projects.

2. While the potential environmental effects of individual projects are evaluated prior to dam construction, there is a need for consideration of the basin-scale ecological consequences of hydropower development. This study was a first attempt to quantify the extent of river fragmentation by dams in the Sarapiquí River Basin.

3. Using simple spatial analyses, the length of river upstream from dams and the length of de-watered reaches downstream from dams was measured. Results indicated that there are currently 306.8 km of river (9.4% of the network) upstream from eight existing dams in the Sarapiquí River Basin and 30.6 km of rivers (0.9% of the network) with significantly reduced flow downstream from dams. Rivers upstream from dams primarily drain two life zones: Premontane Rain Forest (107.9 km) and Lower Montane Rain Forest (168.2 km).

4. Simple spatial analyses can be used as a predictive or planning tool for considering the effects of future dams in a basin-scale context. In the Sarapiquí River Basin, we recommend that future dam projects be constructed on already dammed rivers to minimize additional river fragmentation and to protect remaining riverine connectivity.

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*Correspondence to: Elizabeth Anderson, 11200 SW 8th St., ECS 347, Florida International University, Miami, FL 33199, USA. E-mail: elizabeth.anderson@fiu.edu

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INTRODUCTION

Longitudinal riverine connectivity has long been recognized as critical to the functioning of river ecosystems on a basin scale (Ward, 1989). However, this property has been disrupted in over half of the world's large river systems and an unknown number of smaller river systems by the construction of dams to meet human demands for electricity, water, and flood control (Nilsson *et al*., 2005). Today, more than 45,000 large dams and an estimated 800,000 small dams (<15 m high) exist globally (World Commission on Dams, 2000; McCully, 2001). River basins with only one or no dams are rare in the temperate, northern third of the world where $>75\%$ of the channels of large river systems have been fragmented (Benke, 1990; Dynesius and Nilsson, 1994; Graf, 1999). In the tropics, the extent of river fragmentation by dams remains to be seen. Many tropical rivers are at present unaltered by dams but provisionally selected for extensive development in the future (Pringle *et al*., 2000; Anderson *et al*., 2006b; Greathouse *et al*., 2006). Furthermore, where dams have been constructed in tropical countries, comprehensive assessments of the subsequent losses in longitudinal riverine connectivity on regional, national, or basin scales are rare or non-existent.

In Costa Rica, rivers are increasingly being fragmented as a consequence of a recent expansion in hydropower development. More than 30 new dams have been constructed in Costa Rica since 1990 and at least twice that many additional hydropower projects have been proposed (Braga *et al*., 2000; ICE, 2004; Burgues Arrea, 2005; Anderson *et al*., 2006b). Recent dam construction has been driven by three primary factors: the wealth of freshwater resources and large, untapped hydropower potential; increasing demands for electricity (estimated at $\sim 6\%$ annually); and legislation passed in the 1990s that now allows private companies and rural cooperatives to generate electricity. To date, development has been concentrated in mountainous, humid areas along Costa Rica's northern Atlantic slope and in the San Carlos and Sarapiquí River Basins. By the end of 2005, 27 hydropower plants were in operation on these two basins and at least 10 additional projects were either under construction or being considered (Anderson *et al*., 2006b).

Under the present system of environmental impact assessment in Costa Rica, potential ecological effects of hydropower development are evaluated for individual dams prior to the start of project construction. Detailed studies of the actual ecological effects of individual hydropower plants (post-audits) are uncommon and attempts to examine the effects of multiple dams at a basin scale are rare or non-existent. Currently, Costa Rican law does not require evaluation of the potential for cumulative ecological effects where more than one dam is constructed on a river network. Sparse ecological information on freshwater ecosystems in Costa Rica also hinders basin-scale assessments. Basic hydrologic records and water quality data do not exist for most rivers, and fish collections made during the 1960s-1980s often provide the only biological data (Bussing, 1998).

In light of current hydropower development trends in Costa Rica, there is a need for quantitative assessments that employ available information to examine the potential cumulative effects of existing and proposed dams on broader scales (e.g. river basin) than is currently being realized. The study presented here is a first step to address this need and focuses on the Sarapiquí River Basin, Costa Rica, which has been subject to intensive hydropower development since 1990. This study had two main objectives: (1) to quantify the cumulative extent of fragmentation of the Sarapiquí River network by dams; and (2) to illustrate the utility of simple spatial analyses for basin-scale planning of future hydropower development. The approach presented here may offer insights for other tropical countries experiencing similar patterns of hydropower development and facing similar management challenges.

THE SARAPIQUÍ RIVER BASIN

The Sarapiquí River is a major tributary of the San Juan River, draining a diverse basin (2793 km^2) located on Costa Rica's northern Caribbean slope (Figure 1). The river begins in the highlands of the central volcanic corridor and its course (~ 94 km) spans an altitudinal gradient of >2000 m. Annual precipitation

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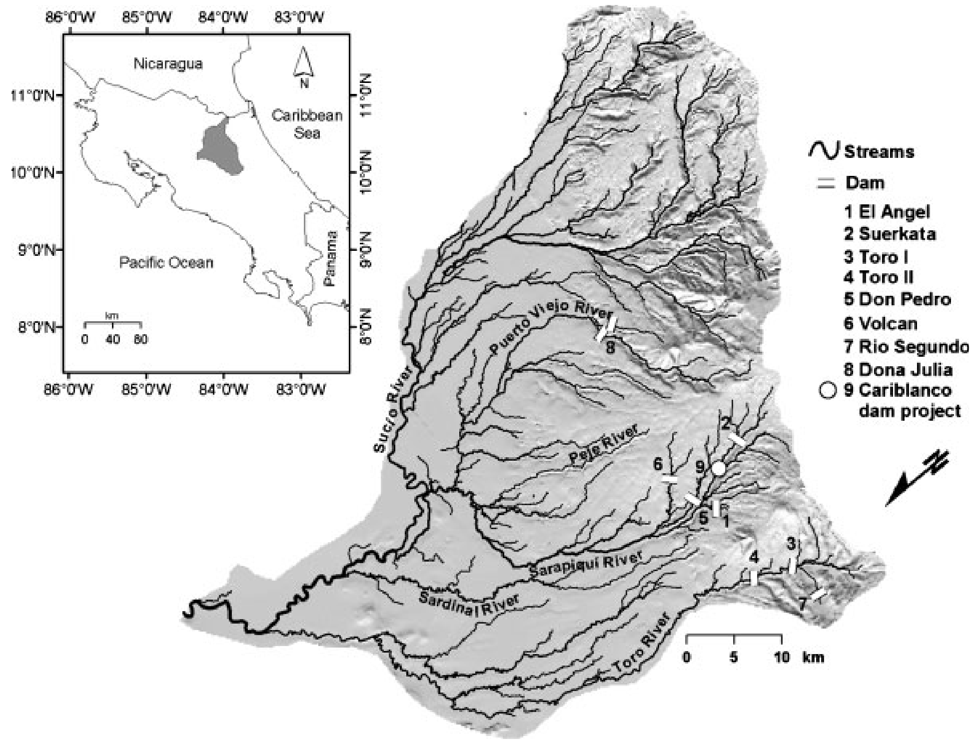

Figure 1. Hydropower development in the Sarapiquí River Basin is concentrated in areas of high topographic relief and average annual precipitation in excess of 4 m. The locations of eight hydropower plants and the general location of the Cariblanco Dam Project (under construction) are indicated on the map (figure by M. Snyder).

varies throughout the Sarapiquí River Basin, from approximately 4 m in the lowlands to 8 m in mountainous areas. Rainfall is more evenly distributed throughout the year than in other parts of Costa Rica, as the basin lacks a distinct 'dry' season (Sanford *et al.*, 1994). The range in altitude and precipitation has helped to create diverse terrestrial and aquatic habitats, such as tropical montane forests, lowland tropical rain forests, and wetlands. Scientific studies of terrestrial biodiversity are numerous, particularly in lowland areas within and surrounding the La Selva Biological Station (see McDade *et al.*, 1994). Comparatively less is known about aquatic biodiversity. Surveys conducted during the 1960s recorded 43 native species of fish from the Sarapiquí River and its tributaries (Bussing, 1993, 1998); crocodiles (*Crocodylus acutus*), caiman (*Caiman crocodilis*), nutria (*Myocastor copyus*), and freshwater shrimp (*Macrobrachium*; *Atya*) are also common in rivers of the basin. Tropical forests once covered the entire Sarapiquí region, but today the landscape is a mosaic of agricultural lands, human settlements, and patches of remnant forests. Consequently, land and water resources are increasingly subject to pressure from human activities (Butterfield, 1994; Anderson *et al.*, 2006b).

The natural features of the Sarapiquí River Basin, particularly high topographic relief, year-round rainfall, and proximity to the capital of Costa Rica (San Jose) have made it a target for hydropower development in recent years. Before 1990, the basin's hydropower potential, estimated at >300 MW, was untapped; between 1990 and 1999, eight hydropower plants were constructed and now collectively exploit nearly half of the estimated practical hydropower potential (Figure 1). Two of these plants are run by the government-owned Costa Rican Institute of Electricity (ICE) and the other six belong to private companies. In 2004, construction began on a ninth project, the Cariblanco Dam which, when finished, will

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include four impoundments: one on the mainstem Sarapiquí and three on other rivers (Figure 1). In addition, one more hydropower project began construction on the General River in late 2004 and several more were in planning phases as of 2006.

Hydropower plants in the Sarapiquí River Basin operate as water diversion dams. Each plant has a concrete dam that blocks and diverts river water from the channel. A plant may have more than one dam if water is diverted from multiple rivers and the majority of the dams are <15 m tall. River water is diverted either directly to downstream turbines or, more commonly, to an off-channel reservoir where it is held until peak generation hours, used to generate electricity, and returned to the river channel. Consequently, abrupt changes in discharge and water temperature in the river channel downstream from the turbines occur several times daily according to peak hours of electricity demand (Anderson *et al*., 2006a).

A substantial ecological consequence of this type of hydropower plant is river fragmentation, which results from two main factors: (1) the presence of dams which present physical barriers to longitudinal movement of water, matter and organisms; and (2) flow reductions in the de-watered reach of river between the dam and the turbines which make this reach physically discontinuous with adjacent upstream and downstream areas. De-watered reaches in the Sarapiquí River Basin typically carry 5–10% of average annual flow, as this was the generally recommended environmental water allocation in Costa Rica when existing hydropower plants were constructed. Previous research at a hydropower plant on the Puerto Viejo River (a tributary of the Sarapiquí River) documented marked changes in aquatic habitat in the de-watered reaches immediately downstream from two small dams (Anderson *et al*., 2006a). Although this study and environmental impact assessment reports have implied that river fragmentation caused by individual dams has substantial ecological consequences, to date there have been no comprehensive attempts to address the cumulative ecological effects of the multiple hydropower plants in operation in the Sarapiquí River Basin.

METHODS

Little information about hydropower development in Sarapiquí River Basin was publicly available at the start of this study. A database of information about hydropower plants was created following site visits to seven (El Angel, Suerkata, Toro I, Toro II, Don Pedro, Volcan, Rio Segundo, Doña Julia) during 1999–2002. At five of these sites, a Trimble Navigation Pathfinder ProXL Geographic Positioning System (GPS) was used to record the location of the dam (water diversion site) and the turbines (water return site). For two of the hydropower plants, Don Pedro and Volcan, the hydropower company provided location data because the steep walls of the river canyon made data collection difficult. The location of the Rio Segundo Hydropower Plant was obtained from the project's feasibility study on file at the Department of Private Generation of the ICE. The ICE also provided coordinates for the location of the Cariblanco Dam project's proposed water diversion dams and water return site.

A digital database of rivers for the basin was developed using topographic maps (1:50,000 scale) and ArcGIS 8.2, a commercial Geographic Information Systems (GIS) program from the Environmental Systems Research Institute, Inc. (ESRI, Redlands, CA). Maps were scanned and geo-referenced, and then used as base images to delineate segments of rivers. ArcView 3.2 (ESRI, Redlands, CA), specifically the '*Create Strahler Stream Order Extension*', was used to ordinate all streams in the basin (Strahler 1952; Lanfear 1990). Coordinates of the water diversion and water return sites of each of the existing hydropower plants were imported into the rivers coverage. At the time research was conducted, topographic maps provided higher resolution detail for the basin when compared with other available sources of information, which included a 90-m resolution digital elevation model derived from the Shuttle Radar Topography Mission (M. Snyder, personal communication).

The digital database of rivers was used to calculate: (1) the total length of river (in km) upstream from each dam; and (2) the length of the de-watered reach of river (in km) between the water diversion and the water return at each hydropower plant. De-watered reaches were considered to be disruptions in

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longitudinal riverine connectivity because of the substantial reductions in discharge (90–95%) in these reaches. Rivers upstream from dams were considered to be discontinuous in an upstream direction at all times and discontinuous in a downstream direction during low and normal flow periods. High flows can overtop dams and temporarily restore connectivity in a downstream direction and typically occur during the wettest months of the year in the basin (July, November, and December).

To examine the isolation of river segments with respect to their location in different ecological life zones in the Sarapiqui River Basin, the Holdridge Life Zone model was used to classify general ecosystem types, and then the length of river upstream from each dam in each life zone was calculated (Holdridge 1947; 1967). The Holdridge Life Zone model uses bioclimatic conditions to characterize natural land cover and environmental conditions and, on the basis of its generality, has been applied throughout the neotropics for ecological mapping, natural resource management, and environmental impact assessment. The justification and underlying assumption of use of the model in this study was that different ecological life zones may contain unique habitats for aquatic biota. While there is a need for more investigation on the applicability of the Holdridge Life Zone model for aquatic systems, it was used here as part of a first step for considering how river fragmentation may be distributed in ecologically different areas of the basin.

RESULTS

The Sarapiquí River network encompasses 3275 km of 1st–6th order rivers as measured from 1:50,000 topographic maps. This analysis calculated that 306.8 km of river are now located upstream from existing dams and therefore discontinuous with downstream areas. Cumulatively, this length corresponds to 9.4% of the total river network and consists primarily of 1st order headwater streams. The Cariblanco Dam Project's four dams, once completed, will isolate an additional 136.1 km of river, and will increase the percentage of the Sarapiquí River network at present upstream from dams to 13.5% of total river length. The analysis also indicated that 30.6 km of river have been de-watered by operation of existing dams; the completion of the Cariblanco Dam Project will de-water an additional 16.2 km of river. Cumulatively, these flow reductions directly affect 46.8 km of river, or 1.4% of the total Sarapiquí River network (Table 1).

As classified by the Holdridge Life Zone model, eight different ecological life zones are found in the Sarapiquí River Basin (Table 2). Most of the river network drains one of three major life zones: Wet Tropical Forest (32%), Premontane Rain Forest (24.7%) and Lower Montane Rain Forest (17.5%). Six of the eight life zones in the basin are present in areas upstream from existing dams (Table 2). Rivers upstream from dams primarily drain Premontane Rain Forest (107.9 km; 35.2% of river length upstream from dams) and Lower Montane Rain Forest (168.2 km; 54.8% of river length upstream from dams). The Cariblanco Dam project will influence streams in five of six life zones already affected by hydropower development. Once Cariblanco is completed, all rivers draining Lower Montane Wet Forest and Montane/Lower Montane Transitional Rain Forest in the basin will be located upstream from dams (Table 2).

DISCUSSION

Through simple spatial analysis, this study provided a first step towards basin-scale assessment of the effects of hydropower development on the Sarapiquí River Basin. The strength of the approach presented here lies in its use of information and technologies that are widely available and easy to employ, and the scale at which it was completed. Studies like this that quantify river fragmentation on a basin-scale, rather than a country or regional scale, may illuminate the effects of dams on a level at which water resources are frequently managed.

Nevertheless, the analysis presented here should not be viewed as a substitute for the use of more sophisticated spatial and hydrological techniques that exist for examining the effects of dams where

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Table 1. Fragmentation of Sarapiquí River network by hydropower plants

River	Length of river de-watered (km)	Total length of river upstream (km)	Upstream river km (% total)			
			1st order	2nd order	3rd order	4th order
Existing hydropower plants						
Angel River	0.9	36.4	23.9 (1.3)	12.0 (1.9)	0.5 (0.1)	
Sarapiqui River	1.1	26.3	18.0 (1.0)	5.8 (1.0)	2.5 (0.6)	
Toro River	5.2	72.2	48.4 (2.6)	17.2 (2.7)	6.6 (1.6)	
Gata Stream	1.6	15.3	14.3 (7.7)	1.1 (0.2)	0	
San Fernando River	6.4	37.7	22.4 (1.2)	9.5 (1.5)	5.8 (1.4)	
Volcan River	7.4	38.5	28.2 (1.5)	9.0 (1.4)	1.3 (0.3)	
Segundo River*	1.9	8.5	7.2 (0.4)	1.3 (0.2)	0	
Puerto Viejo River	4.1	71.2	45.9 (2.5)	12.4 (1.9)	12.9 (3.1)	
Quebradon stream	2.0	7.2	7.2 (0.4)	0	0	
Subtotal	30.6 (0.9)	306.8 (9.4)*	208.3 (11.2)*	67.0 (10.4)	29.6 (7.2)	
Projected effects of Cariblanco dam						
Sarapiqui River**	9.3	108.4	68.4	22.8	12.9	4.3
Maria Aguilar River	3.2	9.1	8.7	0.4	0.0	0.0
Cariblanco River	2.1	27.0	24.2	2.4	0.4	0.0
Quicuyal River	1.6	17.9	12.5	5.5	0.0	0.0
Subtotal**	16.2 (0.5)	162.4 (5.0)	106.8 (5.7)	31.1 (4.8)	13.3 (3.2)	4.3 (2.1)
Total	46.8 (1.4)	442.9 (13.5)	297.1 (15.9)	92.3 (14.3)	39.9 (9.7)	4.3 (2.1)

Note: Length of river de-watered and upstream from dams in the Sarapiquí River network. % total refers to the percentage of total length of that order of streams (using the Strahler Stream order) in the entire network.
*The Segundo River basin is a sub-basin of the Toro River. Thus, the length of river upstream from this dam is not included in the total since it was already accounted for in the length of river upstream on the Toro River.
**Totals for length of river upstream overlap with calculations for the Suerkata Hydropower Plant, also located on the Sarapiqui River. After subtracting this length of river, the projected additive impacts of Cariblanco on a basin-scale are 136.1 km total length of river upstream; 88.8 km of 1st order streams; 25.3 km of 2nd order streams; 10.3 km of 3rd order streams.

Table 2. Length of river (km) upstream from dams in different ecological life zones

Holdridge life zone	Length of river in network (% of total network)	Length of river upstream from existing dams (% of river length draining life zone in network)	Cumulative total length of river upstream (km) with Cariblanco Dam (% of river length draining life zone in network)
1. Lower Montane Wet Forest	33.7 (1.02)	20.1 (59.6)	33.7 (100.0)
2. Premontane Wet Forest	352.5 (10.76)	0.0	0.0
3. Wet Tropical Forest	1063.7 (32.47)	0.0	0.0
4. Wet Tropical Forest transition to Premontane Wet Forest	369.7 (11.28)	2.4 (0.7)	2.4 (0.7)
5. Montane Rain Forest	72.8 (2.22)	2.36 (3.2)	7.3 (10.0)
6. Lower Montane Rain Forest	573.4 (17.50)	168.2 (29.3)	248.5 (43.3)
7. Montane/Lower Montane transitional Rain Forest	2.4 (0.07)	1.07 (44.5)	2.4 (100.0)
8. Premontane Rain Forest	807.6 (24.65)	107.9 (13.3)	148.7 (18.4)

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required data are available. We recommend that more comprehensive techniques for basin-scale assessments continue to be developed, especially those that take into account cumulative hydrologic alterations and their subsequent effects on aquatic biota.

This study showed that hydropower development in the Sarapiquí River Basin is concentrated on low-order streams and has resulted in substantial discontinuities between the downstream segments of large rivers in the basin (Sarapiquí, Puerto Viejo, Toro Rivers) and their headwater drainage networks. The analysis has almost certainly underestimated the length of river upstream from dams, since it was based on 1:50,000 scale topographic maps. As many as 80% of headwater, ephemeral, and intermittent streams are not mapped at this scale (Meyer and Wallace, 2001); however, a finer scale of map was not available for the basin at the time of the analysis. In reality, the length of river upstream from dams may be more than double the estimate reported here.

Although dams in the Sarapiquí River Basin may be located in the upper and middle parts of the basin, the consequent ecological effects of river fragmentation are probably transferred to other parts of the network. The ecological role of headwater systems in a river network has long been underestimated, despite the fact that headwater streams provide unique habitats for aquatic biota and are important sources of sediment, nutrients, and organic matter for downstream areas (Meyer and Wallace, 2001; Gomi *et al.*, 2002). In the case of the Sarapiquí River Basin, it is certain that dams hinder longitudinal movement of biota and downstream export of matter and nutrients. Observations made during a study at the Doña Julia Dam on the Puerto Viejo River in the south-eastern part of the basin provide some evidence: migratory freshwater shrimp (*Macrobrachium* spp. and *Atya* spp.) appeared to be absent upstream of an 8 m high dam, but were commonly found in nearby downstream areas (E. Anderson, unpublished data). In addition, after only 3 years of operation, trapped sediment behind the dam had already become a management concern and there were visible increases in the amount of exposed bedrock immediately downstream from the dam.

De-watering of rivers downstream from dams could eventually affect distribution and long-term survival of aquatic biota in the Sarapiquí River Basin, especially on the basis of habitat alterations. De-watered reaches are characterized by slower water velocities, warmer water temperatures, and shallower habitats than adjacent upstream and downstream areas (Anderson *et al.*, 2006a). For aquatic biota, these conditions might resemble those of a prolonged drought. Past research on effects of drought on neotropical stream biota has suggested that extended low-water periods significantly alter aquatic communities through localized crowding of aquatic biota into severely reduced habitat; this crowding affects long-term survivorship through decreased reproduction or increased predation pressure (Covich *et al.*, 2003). One important characteristic about dams in the Sarapiquí River Basin is that most allow high flows to pass over the dam. While there may be advantages to the maintenance of this flow variability (Poff *et al.*, 1997), the rate of change and magnitude of the flow differences between disturbance and normal conditions is greater in the de-watered reach than in adjacent upstream and downstream areas. Consequently, disturbance events, such as high flows and floods, may play more of a role in shaping biotic assemblages in de-watered reaches than they would in the absence of a dam. In the Sarapiquí River Basin, studies from the Puerto Viejo River near Doña Julia Dam suggested that physical conditions in the de-watered reach favour tolerant fish species with opportunistic-type life histories over species with more complex reproductive requirements. In addition, larger fish species commonly found in undammed rivers of similar size (e.g. *Joturus pichardi*, *Brycon guatemalensis*, *Sicydium altum*) were not encountered in the Puerto Viejo River near the dam site during the study (Anderson *et al.*, 2006a). More research is needed to examine how long periods of drought-like conditions interrupted by high flows may influence aquatic biota in de-watered reaches and how potential effects multiply across a river network as more dams are constructed.

Examining the relative effects of hydropower development on longitudinal riverine connectivity in different life zones provided ecological information not obtained by simply quantifying the length of river de-watered or located upstream from dams. Hydropower plants in the Sarapiquí River Basin are

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concentrated within a relatively narrow range of elevations and climatic conditions, with rivers upstream from dams draining two dominant life zones (Premontane Rain Forest and Lower Montane Rain Forest). Rivers in these zones are characterized by cool water temperatures and cobble-boulder bed sediments, and harbour assemblages of fish and aquatic insects that are different from those found in rivers draining the extensive lowland areas of the basin. For example, *Priapichthys annectens* (Poecilidae), a fish endemic to Costa Rica, is one of the common species found to inhabit streams draining Montane Rain Forest and Premontane Rain Forest life zones near dams. *Joturus pichardi* (Mugilidae) and *Sicydium altum* (Gobiidae) are migratory fish commonly found in these rocky, cold-water streams (Bussing, 1998). These species may be especially vulnerable to fragmentation and habitat alteration resulting from hydropower development in this portion of the basin. Although the use of the Holdridge Life Zone model may be appropriate for coarse-level assessment and for identifying areas most susceptible to effects of hydropower development, finer, more detailed studies of abundance, distribution, and life-history are necessary to determine if and how river fragmentation and hydrologic alterations associated with dams affect these and other aquatic biota.

Considering longitudinal river connectivity when planning future hydropower dam projects

As more hydropower dam projects are constructed and planned for the Sarapiquí and other Costa Rican river basins, there is an increasing need for examination of the effects of hydropower development beyond the individual dam level during the project planning and design phase. The extent of additional river fragmentation is affected by the placement of new projects relative to existing dams in a river network. Consideration of new projects within a basin context can help to identify sites that maximize electricity generation while minimizing losses in longitudinal riverine connectivity. Toward this end, the methods used in this study for quantifying river fragmentation by existing dams can also be applied for comparison of alternative hydropower development scenarios on a river basin scale.

To illustrate this application, the fragmentation effects of two hypothetical dam projects on rivers in the Sarapiquí River network were compared. Sites for these hypothetical projects were selected based on elevation and slope characteristics and how similar these conditions were to the elevation ($\sim$950 m.a.s.l.) and slope ($\sim 38^\circ$) of the location of the Cariblanco Dam. The first hypothetical project, Dam 1, was placed on the Toro Amarillo River in the south-eastern part of the Sarapiquí drainage at an elevation of 959 m.a.s.l. and a slope of 35°. The second project, Dam 2, was placed on the Toro River in the western part of the basin at an elevation of 851 m.a.s.l. and a slope of 45°. Employing the same methods and database used to examine the effects of existing dam projects on longitudinal riverine connectivity, it was calculated that Dam 1 would fragment 83.1 km of river in three life zones located upstream from the hypothetical location: Premontane Rain Forest (13.4 km), Lower Montane Rain Forest (44.5 km), and Montane Rain Forest (25.2 km). Dam 2 would have a greater individual impact on longitudinal riverine connectivity by fragmenting 121.6 km of river in five life zones: Premontane Rain Forest (32.6 km), Lower Montane Rain Forest (73.4 km), Lower Montane Wet Forest (13.3 km), Montane Rain Forest (1.2 km), and Montane/Lower Montane Transitional Rain Forest (1.1 km).

These two hypothetical projects illustrate the importance of considering the effects of future dams on longitudinal riverine connectivity in a basin context. Although Dam 1 may have a smaller individual impact, the additive effects on the overall connectivity of the Sarapiquí River network are greater than those of Dam 2. Because Dam 1 would be located on an unaltered river, its construction would increase the cumulative percentage of the Sarapiquí network upstream from dams from 13.5% to 16.9% of the total length of river. However, the additive effect of Dam 2 on total length of fragmented rivers in the basin would be less (increase from 13.5% to 15.4% of total length of river), because of its location downstream from the Toro I and II Hydropower Plants. Furthermore, Dam 1 would substantially increase the cumulative effect of hydropower developments on rivers draining Premontane (from 13% to 15% of network total), Lower Montane (from 29% to 37%), and Montane Rain Forest (from 10% to 45%).

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Dam 2 would result in increases of affected length of river in only two life zones: Premontane (from 13% to 16%) and Lower Montane Rain Forest (from 29% to 32%). On the basis of this simple analysis, we recommend that future dam projects in the Sarapiquí River Basin be constructed on already altered rivers to minimize additional river fragmentation and avoid the total loss of intact habitat in ecological life zones in the band of elevations and climatic conditions where hydropower developments are heavily concentrated.

Hydropower development trends in other Mesoamerican and Caribbean Island river basins may mirror those of the Sarapiquí River Basin in the near future. Hundreds of new hydropower projects are currently proposed or beginning construction in these regions (Burgues-Arrea, 2005; Anderson *et al*., 2006b; Greathouse *et al*., 2006) and the resulting extent of river fragmentation remains to be seen. A shift towards a more basin-scale approach in planning and impact assessment of dams will be necessary for minimizing losses in longitudinal riverine connectivity and its subsequent ecological effects.

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