Optimizing hydropower dam location and removal in the São Francisco River basin, Brazil to balance hydropower and river biodiversity tradeoffs

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Abstract

To support eco-friendly hydropower planning in developing regions, we propose a spatial optimization model for locating dams to balance tradeoffs between hydropower generation and migratory fish species richness. Our model incorporates two special features. First, it is tailored to the dispersal of tropical migratory fishes, which require long, unimpeded river stretches to complete their life-cycle. To model fish with this type of dispersal pattern, we introduce the concept of a river pathway, which represents a novel way to describe river connectivity. Second, it combines decisions about dam placement and removal, thus facilitating opportunities for hydropower offsetting. We apply our model to the São Francisco River basin, Brazil, an area of hydropower-freshwater biodiversity conflict. We find that dams have reduced weighted migratory fish richness 51% compared to a pre-dam baseline. We also find that even limited dam removal has the potential to significantly enhance fish biodiversity. Offsetting the removal of a single dam by the optimal siting of new dams could increase fish richness by 25% above the current average. Moving forward, optimizing new dam sites to increase hydropower by 20%, rather than selecting the fewest number of dams, could reduce fish species losses by 89%. If decisions about locating new dams are combined with dam removal, then a win-win can even be achieved with 20% greater hydropower and 19% higher species richness. Regardless of hydropower targets and dam removal options, a key observation is that optimal sites for dams are mostly located in the upper reaches of the basin rather than along the main stem of the São Francisco River or its main tributaries.

Introduction

Freshwaters are among the most sensitive to human development and the most threatened of all ecosystems (Dudgeon *et al*. 2006). Freshwater vertebrates have experienced severe declines in spatial distribution and abundance (Strayer and Dudgeon 2010), with a 76% average population reduction over the past 40 years (WWF 2014). A principal cause of this decline is habitat loss fragmentation due to the construction of dams (e.g., for irrigation, hydropower, and flood control) and other artificial in-stream structures (e.g., stream-road crossing).

Recent concerns about the effectiveness of traditional mitigation strategies, namely fish passes, challenge conventional wisdom (Brown *et al*. 2013). Fish passes often exhibit lower than expected efficiencies (Noonan *et al*. 2012), unintended consequences (McLaughlin *et al*. 2013), or even negative effects (e.g., the creation of "hotspots" for predation: Agostinho *et al*. 2012; and ecological traps: Pelicice and Agostinho 2008). Part of this failure relates to an overly narrow focus on technical standards, without considering local factors such as the presence of key fish habitats above and below a pass (Pompeu *et al*. 2012) and downstream movement of embryos, larvae, and adults past reservoirs (Pelicice *et al*. 2015). In North America and Europe, alternatives to fish passes, such as complete or partial removal of fish migration barriers, are becoming more frequent. With restoration efforts constrained by limited resources, however, effective methods to prioritize removals at the catchment-scale are critical to achieve conservation objectives.

Various barrier prioritization methods have appeared in recent years (Kemp and O'Hanley 2010). These include simple but inefficient scoring-and-ranking approaches (Kocovsky *et al*. 2009), spatially informed graph theoretic models (Segurado *et al*. 2013), and optimization based techniques (O'Hanley and Tomberlin 2005). Applications are biased, however, to developed, northern temperate regions, where the majority of viable hydropower and water storage potential has already been realized. Installation of new infrastructure is rarely considered, though there are exceptions (Ziv *et al*. 2012; Ioannidou and O'Hanley 2018). Existing methods also frequently apply assumptions appropriate to a limited number of economically important fish taxa, usually with anadromous migrations (e.g., Salmonidae). Unfortunately, such tools cannot be easily transferred to tropical regions, which maintain rich fish communities with more complex life-histories and movement strategies (Carolsfield *et al*. 2003; Hogan *et al*. 2004). There is an urgent need to develop prioritization methods for dam installation and removal that support more sustainable water and energy resource management in tropical regions.

Brazil provides a perfect illustration of a water-energy-fisheries nexus. Per capita income is increasing and rapid urbanization is placing strains on inadequate water and electricity distribution systems. More than 80% of electricity is produced from hydropower. There are plans to develop this resource further. In the Amazon alone, there are 256 hydropower dams (≥1MW) in operation, under construction, or proposed (Little 2014). While helping to reduce poverty and spur economic growth, rapid expansion of large-scale hydropower can negatively affect inland fisheries, a highly valuable ecosystem service in the country. Brazilian rivers are enormously productive and species rich, with well over 2000 identified fish species (Buckup *et al*. 2007). Since 2000, mean non-marine capture fisheries in Brazil have exceeded 200,000MT annually (FAO 2012). Concerns over dam impacts on fisheries and biodiversity are likely to be a continuing source of environmental conflict (Watkin *et al*. 2012).

This study describes the use of a novel spatial optimization model for locating hydropower dams to balance tradeoffs between hydropower generation potential and migratory fish species richness. A case study of the São Francisco River basin is used to explore various hydropower development scenarios and their impacts on riverine fish biodiversity. There are at least two noteworthy aspects of our model. First, whereas existing barrier optimization tools are designed exclusively for migratory fish in northern latitudes (Kuby *et al*. 2005; Neeson *et al*. 2015; King *et al*. 2017), our model is tailored to the unique dispersal patterns of tropical migratory fish species. Such species generally require long, unimpeded stretches of free-flowing river to complete their life-cycle. To model fish with this type of dispersal pattern, we introduce the concept of a river pathway. The use of river pathways represents a novel way to describe river connectivity that contrasts markedly from existing river connectivity metrics. Second, current models focus exclusively on removal/mitigation of existing barriers (Neeson *et al*. 2015) or, in a limited number of cases, the location of new dams (Ziv *et al*. 2012; Ioannidou and O'Hanley 2018). In contrast, our model combines both dam placement and removal decisions. This is particularly useful for investigating how hydropower offsetting could be used to achieve biodiversity gains, while maintaining or expanding hydropower generation potential (Owen and Apse 2015).

Methods

Study Area

The São Francisco (Figure 1) is the 25th longest river in the world (Tan and Sheng 2004). The basin covers 7.4% (631,133 km^2) of Brazil between latitudes 7°S and 21°S (Knoppers *et al*. 2006). Primary water uses include power generation, irrigation, urban/industrial water supply, navigation, and fishing. Downstream of Três Marias dam, floodplains along the São Francisco occupy approximately 2000km^2 (Welcomme 1990), supporting one of the most important inland Brazilian fisheries (Sato and Godinho 2004).

[Figure 1 approx. here]

Since the 1950s, the São Francisco River has been dammed for energy generation and flow regulation. Presently, there are 28 large (≥30MW) hydropower dams and dam complexes (hereafter dams) across the basin supplying 10.8GW of installed generation capacity. There are at least 117 proposed development sites, which if built would provide an additional 3.9GW (+27%) of hydropower. The vast majority of these candidate sites are concentrated in the upper reaches of the basin to the west and south.

Migratory Fish Species Richness and Abundance

In tropical areas, such as the São Francisco, migratory freshwater fish are mostly pelagic-broadcast spawners. Each year, adults migrate upstream, sometimes hundreds or even thousands of kilometers, to spawn and then migrate back downstream (Godinho and Pompeu 2003). Embryos and larvae drift passively downstream until developing into free-swimming juveniles, before eventually seeking out floodplains to complete their rearing. This is distinct from the spawning strategies typical of migratory fish species in temperate areas (e.g., salmon, *Oncorhynchus* sp., and sturgeon, *Acipenseridae* sp.), where fertilized eggs are actively deposited in (brood hiders) or subsequently adhere to (benthic spawners) the substrate.

Tropical migratory fish usually require long stretches of river (10s to 1000s of kilometers) with unimpeded flow. The presence of dams, which block upstream migrating adults or cause downstream dispersing embryos/larvae to drop out of suspension after encountering large reservoirs, can cause rapid declines in species richness (Pelicice *et al*. 2015).

[Figure 2 approx. here]

We modeled richness for 12 native migratory fish species in the São Francisco as function of river length (Appendix A). To do so, we introduce the concept of a river “pathway.” A pathway is the longest continuous stretch of river in the direction of flow unimpeded by dams or reservoirs. A pathway is uniquely identified by its terminal upstream and downstream segments, starting either at the river headwaters or immediately downstream of a dam and ending either immediately above the first downstream reservoir or the river mouth (Figure 1). Based on Zambaldi and Pompeu (*Under review*), pathways were subdivided into three size classes and assigned species richness estimates proportional to size (Table 1).

[Table 1 approx. here]

While river length is an important determinant of richness, access to floodplains, which provide productive areas for juvenile rearing, has been shown to regulate migratory fish abundance (Nestler *et al*. 2012). To incorporate the importance of floodplain access, we estimated floodplain area within 1km of the river channel and allocated pathways into one of four classes, giving extra weight to pathways connected to larger floodplains (Table 2).

[Table 2 approx. here]

Geospatial Data Processing

Input data for the hydropower dam optimization model were derived in a series of processing steps using ArcGIS and GRASS (Appendix B). A flow-directed river network was produced based on topological data obtained from Weber *et al*. (2004). Strahler stream order of each segment was then determined and all segments of order 3 or less subsequently removed. We also determined the Shreve order of each segment using the RivEX toolbox for ArcGIS (Hornby 2014).

Spatial coordinates and hydropower generation potential of all existing/proposed hydropower dams were taken from the Brazilian Electricity Energy Regulatory Agency database (SIGEL/ANEEL 2016). For several dam complexes sharing a common reservoir, individual dams were merged into a single location and their generation potential added together. The Barrier Analysis Tool (BAT) add-in for ArcGIS (Hornby 2013) was then used to snap dam locations (50m snapping distance) to the river network and split the network at each dam site. After snapping, a total of 28 existing and 117 proposed dam sites were identified.

Reservoir polygons were created using a specially coded Python script for estimating impounded area above dams. Reservoir polygons were then intersected with the river network to determine portions of the river currently impounded by existing dams or would become impounded if proposed dams were built. In cases where no appreciable reservoir was produced, a dummy segment (length 0m) was inserted into the river network just upstream of the dam (for delineating the terminal segment of a river pathway). The final river network was composed of 13,246 confluence and reservoir bounded river segments (including dummy segments).

Floodplains were mapped using Landsat 8 OLI imagery. A 1km lateral buffer was placed around each river segment to obtain the area of nearby floodplain. Finally, a specially coded C++ routine was used to extract all existing/potential river pathways ($n = 6021$) within the river network.

Hydropower Dam Optimization Model

To strategically locate and remove hydropower dams, we develop a spatial optimization model to maximize mean weighted migratory fish species richness within a planning region subject to targets on hydropower generation potential and number of dam removals. We assume that the river network is composed of a set of confluence and reservoir bounded river segments. Species richness in non-impounded river segments is determined based on river pathway length, with longer pathways supporting higher richness. Pathways and their constituent river segments are given proportionally higher weight depending on the amount of accessible floodplain (a proxy for fish abundance). Weightings are also given to river segments based on Shreve stream order.

[Table 3 approx. here]

To develop a mathematical formulation of our hydropower dam location/removal model, we use the notation provided in Table 3 and the following decision variables.

$$x_j = \begin{cases} 1 & \text{if hydrowpower dam } j \text{ is present} \\ 0 & \text{otherwise} \end{cases}$$

$$y_f = \begin{cases} 1 & \text{if pathway } f \text{ is barrier-free} \\ 0 & \text{otherwise} \end{cases}$$

$$z_{s\ell k} = \begin{cases} 1 & \text{if segment } s \text{ is assigned to a barrier-free pathway of size class } \ell \\ & \text{and floodplain class } k \\ 0 & \text{otherwise} \end{cases}$$

Variables $z_{s\ell k}$ perhaps require a bit of further explanation. In general, river segments can potentially lie along multiple barrier-free pathways of varying size and floodplain class. As an example, consider the pathways 9⇾5 and 11⇾5 shown in Figure 2, with pathway 9⇾5 forming a subpath of 11⇾5. If dam C were constructed, then segments 5 and 9 would necessarily be part of the pathway 9⇾5, since pathway 11⇾5 would not be barrier-free. If dam C were not constructed, on the other hand, then pathways 9⇾5 and 11⇾5 would both be barrier-free at the same time. Logically, segments 5 and 9 should form part of the longer pathway 11⇾5. However, as the optimization model needs to evaluate all feasible pathways a choice must, in fact, be made in the event dam C is not built: “assign” segments 5 and 9 to pathway 11⇾5 or to pathway 9⇾5? Variables $z_{s\ell k}$ help to keep track of which pathway each segment is ultimately assigned to. Additional constraints within the model (discussed below) ensure every segment is assigned to one and only one pathway, thus preventing double counting (e.g., segments 5 and 9 being simultaneously assigned to pathways 9⇾5 and 11⇾5).

With this in place, a mixed integer linear programing formulation of our model is then given as follows.

$$\max \frac{1}{V} \sum_{s \in S} \sum_{\ell \in L} \sum_{k \in K} v_s w_k R_\ell z_{s\ell k} \tag{1}$$

$s.t.$

$$\sum_{j \in J} h_j x_j \geq \theta H' \tag{2}$$

$$\sum_{j \in J'} x_j \geq n' - m \tag{3}$$

$$x_j + x_t \leq 1 \qquad \forall j \in J, t \in E_j \tag{4}$$

$$y_f + x_j \leq 1 \qquad \forall f \in F, j \in B_f \tag{5}$$

$$z_{s\ell k} \leq \sum_{f \in P_{s\ell k}} y_f \qquad \forall s \in S, \ell \in L, k \in K \tag{6}$$

$$\sum_{\ell \in L} \sum_{k \in K} z_{s\ell k} \leq 1 \qquad \forall s \in S \tag{7}$$

$$x_j \in \{0,1\} \qquad \forall j \in J \tag{8}$$

$$y_f \geq 0 \qquad \forall f \in F \tag{9}$$

$$z_{s\ell k} \geq 0 \qquad \forall s \in S, \ell \in L, k \in K \tag{10}$$

The objective (1) maximizes mean migratory fish species richness, weighted by access to floodplain areas, within the river network. This is found by summing across all segments (s), pathway size classes (ℓ), and floodplain classes (k) the richness of each pathway (R_ℓ), weighted by effective abundance (w_k) and segment size (v_s), and then dividing by total network size (V). Note that in our case study, segment and total network size are measured as order-weighted length (km), however, in other situations size could be measured as wetted area (km^2) or other some other suitable metric. Constraint (2) requires total hydropower potential to be greater than or equal to some multiple $\theta \geq 0$ of current potential H'. Constraint (3) specifies that no more than m dams can be removed among the n' existing dams. Given the availability of data on dam removal costs, constraint (3) could just as easily be replaced with the constraint:

$$\sum_{j \in J'} c_j \left(1 - x_j\right) \leq b \tag{11}$$

where c_j is the overall cost to remove dam j (including costs associated with feasibility studies, technical planning, demolition, sediment removal, post-removal management, and possibly compensation to dam operators for lost revenue), and b is the available budget for dam removal.

To continue, constraints (4) prevent the nonsensical placement of dams within the "exclusion zone" of any dam site j. The exclusion zone for dam site j (E_j) includes all upstream locations that would be completely submerged (within a reservoir) or whose hydropower potential would be excessively reduced (as a result of backwater effects) due to the construction of dam j. More specifically, if dam j is present ($x_j = 1$), then no dams within its exclusion zone can be present ($x_t = 0$, $\forall t \in E_j$) or if a dam is present in the exclusion zone of j ($\exists t \in E_j | x_t = 1$), then dam j cannot be present ($x_j = 0$). Inequalities (5) state that pathway f can be "active" (i.e., designated barrier-free) if and only if no dam is sited along the length of f ($x_j = 0$, $\forall j \in B_f$). Constraint set (6) stipulates that segment s can only be assigned to a pathway of size class ℓ and floodplain class k ($z_{s\ell k} = 1$) if it lies within at least one active pathway of size class ℓ and floodplain class k ($\exists f \in P_{s\ell k} | y_f = 1$). Inequalities (7) further require that segment s can be assigned to at most one pathway of any size and floodplain class. Finally, constraints (8) place binary restrictions on the x_j dam siting variables, while constraints (9)-(10) require variables y_f and $z_{s\ell k}$ to be non-negative. Note that due to the structure of the model, variables y_f and $z_{s\ell k}$ are guaranteed to take on binary values.

We point out that our use of river pathways to characterize river connectivity based on free-flowing river length differs distinctly from modeling frameworks described previously in the literature. Existing barrier prioritization models are typically designed either to promote diadromous dispersal by enhancing connectivity between the river mouth and areas of river habitats located upstream of barriers (Kuby *et al*. 2005; O'Hanley and Tomberlin 2005; Zheng et al. 2009; Neeson *et al*. 2015; Roy *et al*. 2018) or promote undirected potadromous dispersal (including internal up-down movements and movements between confluent parts of a river) by enhancing connectivity between each and every river habitat area (O'Hanley *et al*. 2013; King *et al*. 2017; Erős *et al*. 2018; Neeson *et al*. 2018).

Structurally, our proposed model is most closely related to O'Hanley (2011), which presents a formulation for maximizing the largest contiguous section of river unimpeded by dispersal barriers. The O'Hanley (2011) model includes variables and constraints, akin to pathway variables y_f and pathway activity constraints (5) described herein, for determining whether two river segments are connected by a barrier-free path and similarly assumes that barriers are completely impassable to fish.

We further observe that our model can be viewed more generally as a multi-objective problem involving the maximization of mean weighted migratory fish species richness ($\max Z_1 = V^{-1} \sum_{s\in S} \sum_{\ell\in L} \sum_{k\in K} v_s w_k R_\ell z_{s\ell k}$), maximization of hydropower generation potential ($\max Z_2 = \sum_{j\in J} h_j x_j$), and minimization of the number of dam removals ($\min Z_3 = n' - \sum_{j\in J'} x_j$). The latter two objectives are incorporated as constraints in the model, as opposed to the common approach of combining all three into a single weighted objective function ($\max \alpha_1 Z_1 + \alpha_2 Z_2 + \alpha_3 Z_3$, with $\alpha_1, \alpha_2 \geq 0$ and $\alpha_3 \leq 0$ being the weights for objectives Z_1, Z_2, and Z_3, respectively). To assess tradeoffs among objectives, one can systematically vary minimum hydropower requirements (θ)

and the maximum number of barrier removals (m'), in order to produce efficient frontiers (i.e., Pareto curves) of mean weighted species richness versus hydropower potential given a specified number of barrier removals. This approach is more formally known as the ε-constraint method for solving multi-objective problems (Cohon 1978).

We implemented our model in the OPL modeling language using CPLEX studio version 12.7.1 (IBM 2017). CPLEX is a state-of-the-art commercial software package that employs branch-and-cut methods to solve mixed integer linear programs (MILPs). All experiments were performed on the same dual-core Lenovo ThinkPad T470 laptop (Intel i7-7600U processor, 2.8GHz per chip) with 32 GB of RAM. Solution times varied from under 1 second to 6.5 minutes, which is remarkable given the large size of the model, which includes 165,118 variables (145 binary) and 203,132 constraints.

Results

A range of tradeoffs exist between mean weighted species richness and hydropower generation potential in the São Francisco for different numbers of dam removals (Figure 3). To structure our analysis, we focus on seven selected hydropower development scenarios: 1) a pre-dam baseline in which the river basin is assumed to be in a fully natural state (Baseline); 2) the current situation given existing dams (Current); 3) an ideal scenario in which dam locations are optimized to achieve current generation potential (Ideal); 4) removal of up to one existing dam combined with optimizing the siting of new dams to compensate for lost hydropower (Offset); 5) a 20% increase in generation potential assuming the fewest number of new dam sites are selected (Future A); 6) a 20% increase in generation potential assuming new dam sites are optimized and no existing dams are removed (Future B); and 7) a 20% increase in generation potential assuming new dam sites are optimized and up to one existing dam can be removed (Future C). Note that comparisons between scenarios are based largely on mean weighted migratory fish richness. Weighted richness (range 2-21 species) accounts for the importance of floodplain access and is, therefore, generally much higher than unweighted richness (range 2-12 species).

[Figure 3 approx. here]

It is clear that hydropower development in the São Francisco has detrimentally impacted fish biodiversity. Weighted richness has been reduced by 51% (from 20.2 species to 9.9 species) compared to a pre-dam baseline (Current versus Baseline, Figure 3). Had dam sites been optimized from the start, average weighted species richness would be 63% higher (+6.2 species) relative to the current value (Ideal, Figure 4a). If one dam can be removed while ensuring hydropower potential is offset by the optimal siting of new dams, then weighted richness could increase 25% (+2.4 species) above the current average (Offset, Figure 4a).

Moving forward, optimizing dam placement and removal could provide substantial benefits in terms of increased hydropower and foregone biodiversity loss. Increasing hydropower potential by 20% would cause weighted richness to decrease a further 10% (-1 species) if dam locations decisions are not optimized (Future A, Figure 4a). When dam placements are optimized, however, only a 1% reduction (-0.1 species) occurs (Future B, Figure 4a). In relative terms, this represents an 89% reduction in richness loss. If up to one existing hydropower dam can be removed at the same time (the Sobradinho dam, Figure 1), then a 20% increase in hydropower could be achieved while simultaneously increasing weighted richness by 19% (Future C, Figure 4a).

[Figure 4 approx. here]

A more in-depth analysis of the results reveals two key insights. The first is that building many small and medium megawatt dams in the upper reaches of the basin would yield substantially better biodiversity outcomes than building a few large megawatt dams along the São Francisco River or its main tributaries. The Offset scenario, for example, achieves higher fish richness compared to the Current scenario by removing one very large dam situated on the main stem (the 1005MW Sobradinho dam) and replacing it with 35 smaller dams (mean 30MW) located mainly on minor tributaries (Figure 5b). Similarly, optimized solutions Future B and Future C, which both produce higher richness compared to non-optimized solution Future A, recommend siting around 12 times the number of new dams as Future A (107-109 versus 9, Figure 4b), with average hydropower per new dam around a tenth (20-29MW versus 240MW). For Future B, no new dams are located on the main stem below Três Marias (Figure 5d). For Future C, only two new dams are found along the main stem below Três Marias (Figure 5e) – one in the lower part of the basin below the Sobradinho, the other a short distance downstream from the Três Marias. Future A, in contrast, locates four dams on the main stem and all but one of the five other dams near the confluences of major tributaries (Figure 5c). Intuitively, the siting pattern for optimized solutions makes sense. Species richness losses for optimized solutions tend to be localized in low-order tributaries, while access to floodplains, which is mostly found along high-order channels, is maintained.

[Figure 5 approx. here]

A second key insight is that even limited dam removal has the potential to significantly enhance fish biodiversity. The Offset and Future C scenarios both produce a significant increase in fish richness (19-25%) with removal of a single dam. These scenarios are not unique in this regard, however. The curve for weighted richness versus hydropower potential given ≤1 dam removal is near optimal (i.e., almost overlaps the ≤28 dam removal curve) for a 15% increase in hydropower or higher, while the curve given ≤2 dam removals is near optimal for current levels of hydropower or higher (Figure 3). What this indicates is that removing just 1-2 dams could return the São Francisco to a near optimal state depending on hydropower requirements.

On this last point, while the benefits of dam removal are unequivocal, what is not so clear is the feasibility of implementing any given set of optimized dam removals in light of attendant costs and other considerations. For example, both the Offset and Future C scenarios recommend removal of the 41m high, 12.5km wide Sobradinho dam. With an installed capacity of 1005MW, the Sobradinho alone accounts for almost 10% of the São Francisco basin's current hydropower potential. It is hard to imagine any realistic scenario in which such a large dam (both in terms of physical size and amount of hydropower) would be removed anytime soon.

[Figure 6 approx. here]

In cases where it is impractical to remove specific dams, supplementary optimization runs can be performed to find a range of alternative options. Indeed, a comparison of the first to fourth best alternative solutions given a 0% or 20% increase in hydropower and up to one dam removal (Figure 6) reveals that the next best alternative yields a similar level of improvement in weighted species richness as the first best alternative (20% versus 25% increase in richness given a 0% increase in hydropower, 17% versus a 19% increase in richness given a 20% increase in hydropower). In both cases, the dam slated for removal is the Três Marias dam. While the Três Marias would certainly be classed as a very large hydropower dam (396MW), it is much older than the Sobradinho. Completed in 1961 primarily for flood control, irrigation, and navigation (Britski *et al*. 1988), the dam is almost 60 years old. Given that the typical life-span of hydropower dam is 50-100 years (Yüksel 2010), it is not inconceivable to propose removing the Três Marias. What is more, recent droughts have caused major reductions in the dam's reservoir levels and, in turn, effective hydropower potential. As recently as 2016, reservoir volume of the Três Marias was only at 38% of capacity at the end of wet season (BHAZ 2016).

Discussion

Our study testifies to the enormous power of optimization models for improving the efficiency of environmental planning. We find that optimizing the siting of new dams can significantly reduce migratory fish species losses compared to selecting the fewest number of dams. Moreover, when decisions about locating new dams are combined with the option to remove a small number of existing dams, it is possible to create a win-win in which both increased hydropower and increased fish richness are achieved.

Previous studies have shown that benefits of optimization are often most pronounced when planning resources are tight (O'Hanley and Tomberlin 2005). Brazil is currently experiencing an economic downturn with negative growth, which has led to substantial cuts in discretionary government spending, including the environment. Moving forward, the use of optimization to guide and efficiently plan hydropower expansion, while limiting impacts on fragile river ecosystems, could prove immensely beneficial to Brazil and other developing nations.

In point of fact, features of our model make it well suited for informing efficient hydropower development across the wider tropics and subtropics (e.g., the Amazon, Mekong, equatorial Africa), where the vast majority of hydropower dam building expected to be concentrated in the coming years (Grill *et al*. 2015; Winemiller *et al*. 2016). Unlike existing barrier optimization approaches, our model is specifically designed to accommodate the life-cycle patterns common to tropical migratory fish species (i.e., pelagic-broadcast spawners). More importantly, the model is data light – only basic biological information (i.e., estimates of species richness as a function of river length and floodplain size class multipliers) and easy-to-obtain geospatial data (i.e., river network, floodplain area, dam location, and reservoir area data) are required. This is a key advantage as developing countries are often hindered by a lack of high quality data, especially detailed biological information (Groves *et al*. 2002).

We acknowledge that dam removals recommended by our model may not always be practical. For example, given a 0% or 20% increase in hydropower and up to one dam removal, the model recommends removing the Sobradinho dam. The Sobradinho is a very large dam that supplies a significant amount of the basin’s hydropower, making its removal an impossibility given current political and socioeconomic realities. In cases where practical consideration prohibit the removal of specific dams, our model can nonetheless be used to find next best solutions (Lawler 1972) which target the removal of other, less controversial dams. Alternatively, one could consider making a simple change to the model to allow removal of only certain categories of dams, for instance older and or smaller (low megawatt) hydropower dams.

It is worth mentioning at least four simplifications of our study. First, due to a lack of catchment-wide data regarding fish species endemism, we had no choice but to treat equally sized sections of river with equal floodplain access as fungible. Given species distribution data, a more targeted approach to conservation could be adopted that limits losses for species of conservation concern. Second, we did not consider the potential effects of dams on flow regulation. Consequently, our model likely underestimates reductions in weighted fish richness due to the reduction of floodplain areas (Nestler *et al*. 2012). Third, our model does not take into account the importance of how different habitat types are spatially distributed. Separation of spawning and rearing grounds by dams and reservoirs can create source-sink dynamics (Godinho and Kynard 2009) and ecological traps (Pelicice and Agostinho 2008). Incorporating additional autecology and spatial information could reduce the risk posed by confining fish populations within short reaches lacking the full range of critical habitats. Fourth, an interesting modification to our model would be to relax the assumption that dams form total barriers to fish dispersal. For example, reservoirs below critical size thresholds (Pelicice *et al*. 2015) should permit at least a fraction of embryos/larvae to move and potentially supplement richness downstream, whereas fish passes with even limited effectiveness might enable sufficient numbers of adults to pass small dams and access upstream spawning areas. More realistic modeling of fish dispersal could help to identify better opportunities for locating, removing, or mitigating dams that maximize fish biodiversity.

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Table 1. Migratory fish species richness for different river pathway size classes.

Pathway Size Class	Length (km)	No. of Species
Small	<50	2
Medium	50 – 100	6
Large	≥100	12

Table 2. Migratory fish species abundance weightings based on access to different floodplain area classes.

Floodplain Size Class	Area (km^2)	Weighting
None	0	1.00
Small	<175	1.10
Medium	175 – 550	1.25
Large	≥550	1.75

Table 3. Model notation.

Set/Parameter	**Definition**
S	Set of river segments within the river network, indexed by s
F	Set of river pathways, indexed by f
L	Set of pathway size classes, indexed by ℓ
K	Set of floodplain size classes, indexed by k
$P_{s\ell k}$	Subset of pathways of size class ℓ and floodplain class k containing segment s
J	Set of existing and candidate hydropower dam sites, indexed by j
J'	Subset of existing dam sites
B_f	Subset of intervening dam sites along pathway f
E_j	Subset of dam sites (possibly empty) in the upstream exclusion zone of site j, indexed by t
v_s	Size (order-weighted length) of river segment s, where $v_s = d_s o_s$, with d_s being the length (km) and o_s the Shreve order of segment s
V	Total size of the river network (km), where $V = \sum_{s\in S} v_s$
R_ℓ	Number of migratory fish species in pathway size class ℓ (range 2-12, see Table 1)
w_k	Migratory fish abundance weight for pathways of floodplain size class k (range 1-1.75, see Table 2)
n'	Number of existing hydropower dams, such that $n' = \lvert J' \rvert$
h_j	Hydropower generation potential of dam site j (MW)
H'	Total hydropower potential of all existing dams (MW), where $H' = \sum_{j\in J'} h_j$

θ	Parameter for controlling required hydropower potential
m	Upper limit on the number of existing dams that can be removed

Figure Captions

Figure 1. The São Francisco River basin showing existing and potential hydropower sites.

Figure 2. Example river network with dams shown as small lettered rectangles. Dams A and B are existing structures (solid lines), dam C is a proposed structure (dashed lines). Blue shaded areas above each dam depict reservoirs (solid lines for existing, dashed lines for proposed). The river network is split into a total of 16 river segments (numbered 1 to 16) based on confluence and reservoir bounding points. All four possible pathway types are shown (dashed orange curves). Starting/ending segments 16 and 1 form a "terminus-to-mouth" pathway (denoted 16→1), 11→5 is a "terminus-to-above reservoir" pathway, 2→1 is a "below dam-to-mouth" pathway, and 6→5 is a "below dam-to-above reservoir" pathway. If dam C were installed, then pathway 11→5 would be split into two new pathways 11→11 and 9→5. If dam B were removed, then pathways 8→8 and 6→5 would be replaced by a new pathway 8→5.

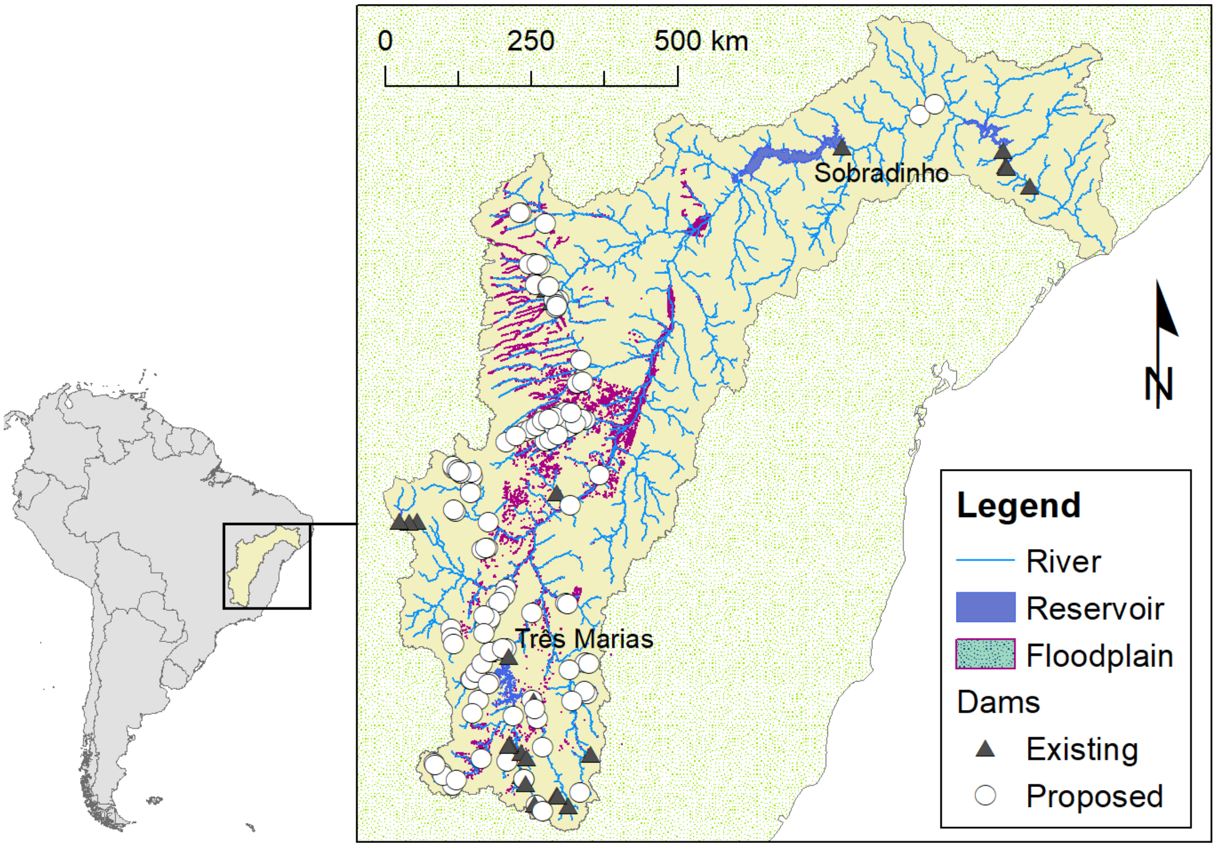
Figure 3. Efficient frontiers of mean weighted migratory fish species richness versus hydropower generation given removal of 0, ≤1, ≤2, and ≤28 (all) existing dams. A hydropower multiplier θ equal to 1 corresponds to current generation potential. Values of θ greater than (less than) 1 corresponds to increased (reduced) generation potential. Scenarios Baseline, Current, Ideal, Offset, Future B, and Future C represent specific solutions along the different efficient frontiers with the curve for ≤28 removals representing the theoretical maximum for mean weighted richness that could be achieved for any desired level of hydropower potential. Scenario Future A falls below the efficient frontier since dam locations are not optimized for this scenario.

Figure 4. Percent change in mean weighted migratory fish species richness relative to current (a) and number of existing/new dams (b) for select dam development scenarios.

Figure 5. Spatial layout of existing and new dam locations and resulting mean weighted migratory fish species richness of river pathways in the São Francisco basin for the scenarios Current (a), Offset (b), Future A (c), Future B (d), and Future C (e).

Figure 6. Percent change in mean weighted migratory fish species richness relative to current for the first to fourth best optimal solutions given a 0% increase (a) or 20% increase (b) in hydropower generation potential and up to one barrier removal. Given a 0% increase in hydropower, the first best solution corresponds to the Offset scenario. Given a 20% increase in hydropower, the first best solution corresponds to the Future C scenario. For each hydropower target, second to fourth best solutions were found by iteratively adding additional constraints that prevented the optimization model from finding the previous solution.

568 [Figure 1]



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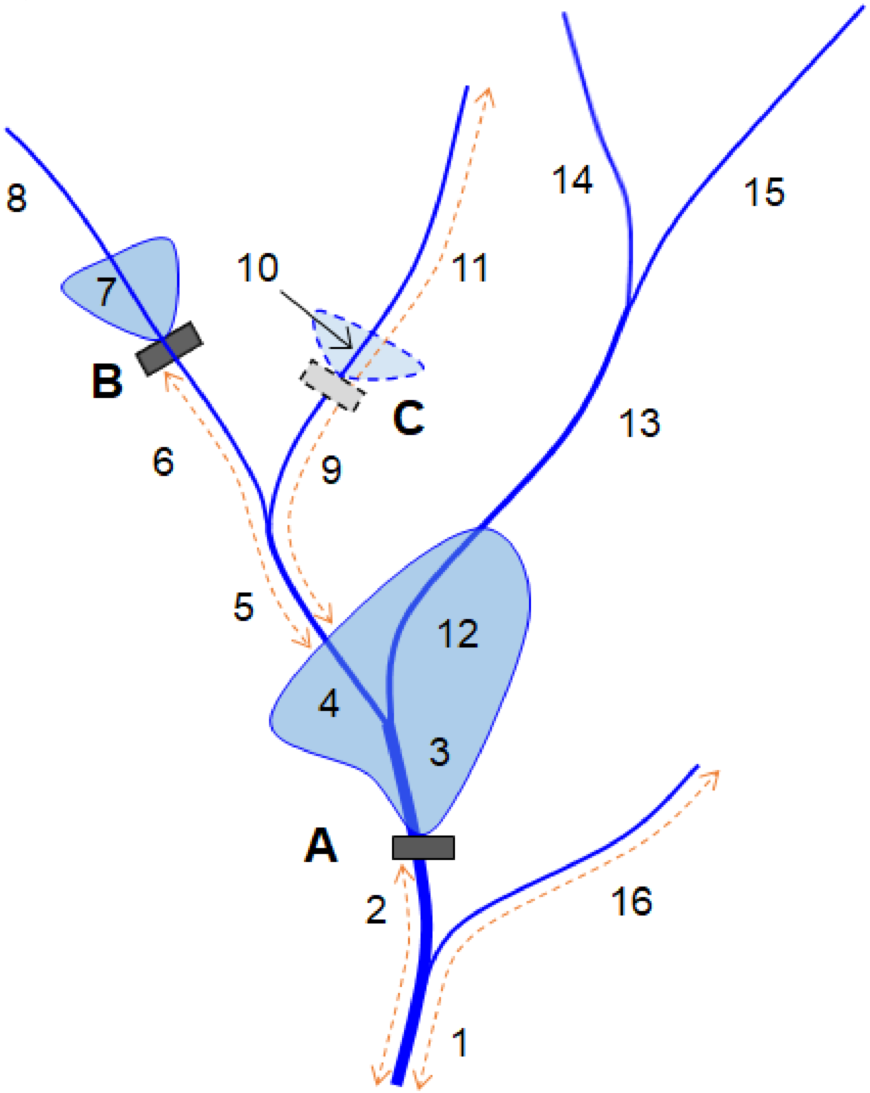
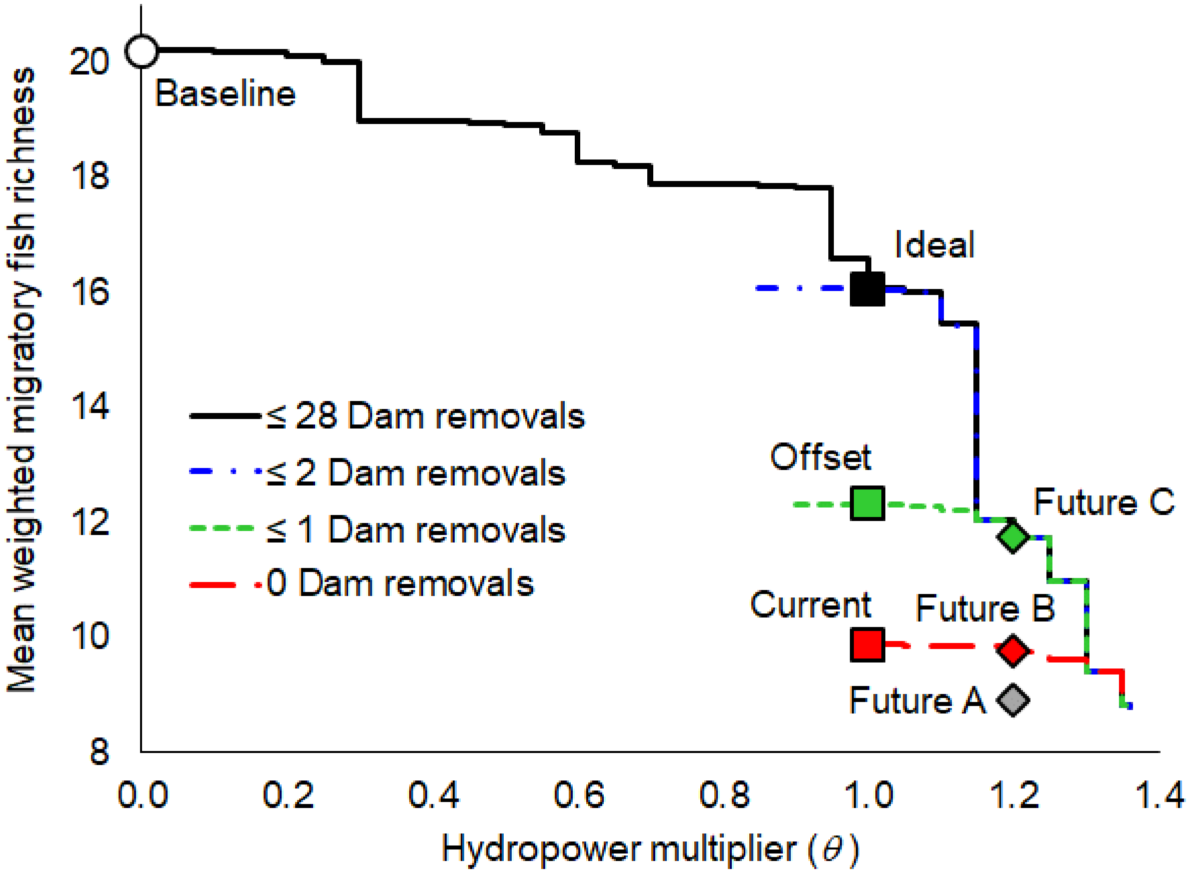
[Figure 2]

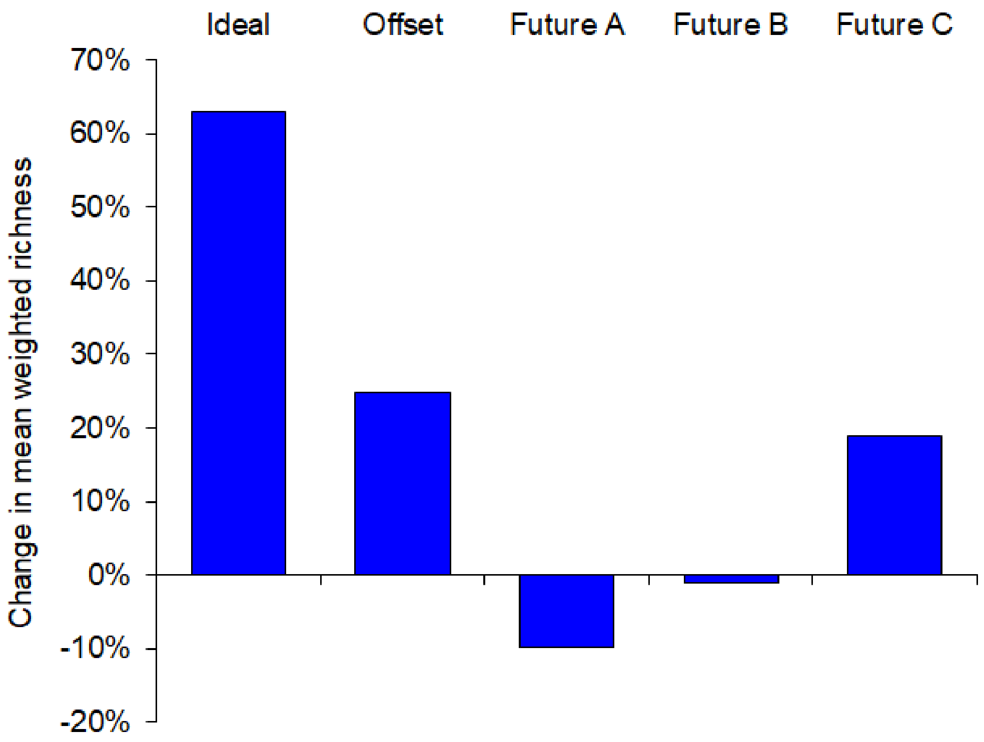


572 [Figure 3]

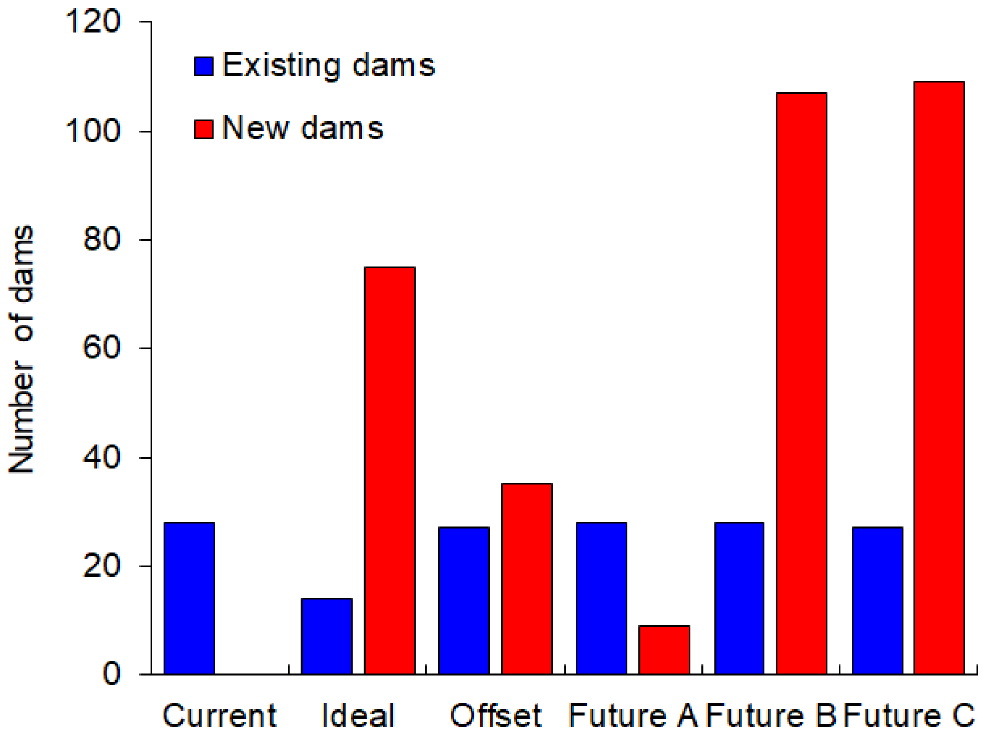


573

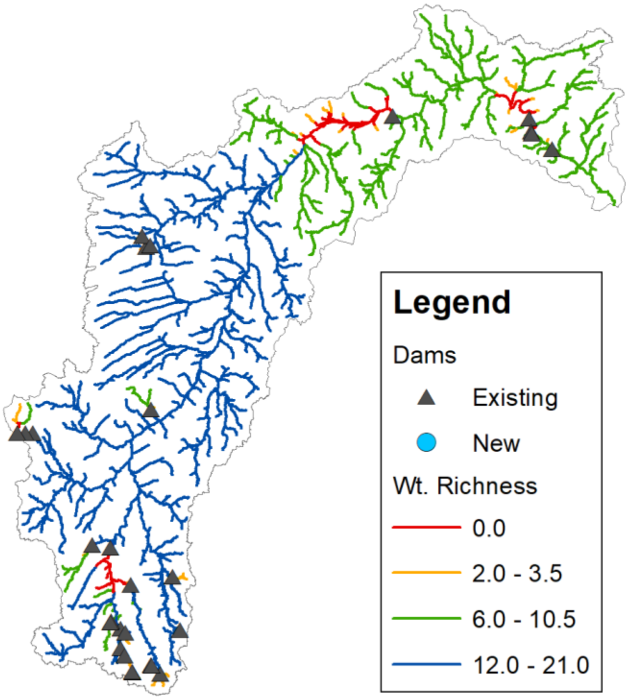
[Figure 4a]



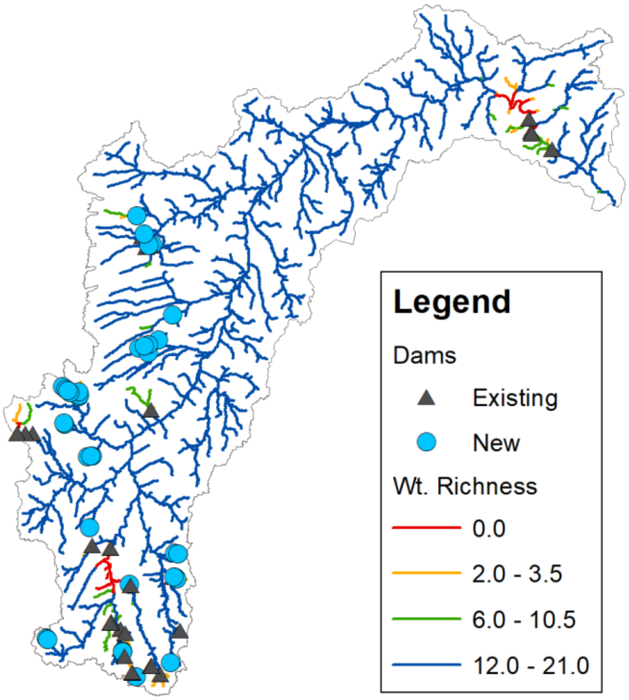
[Figure 4b]



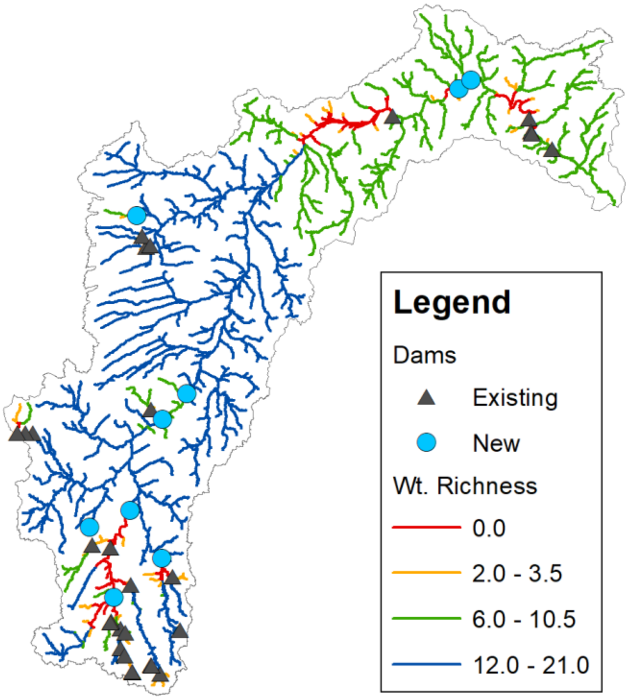
[Figure 5a]



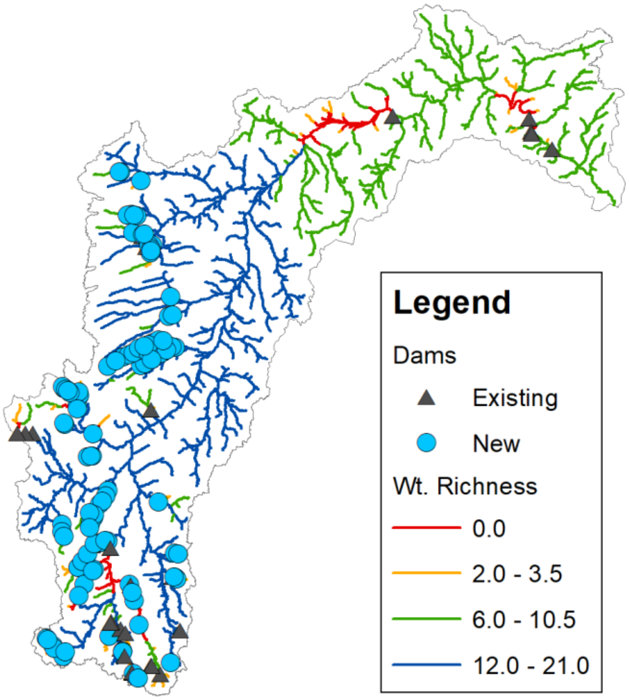
[Figure 5b]



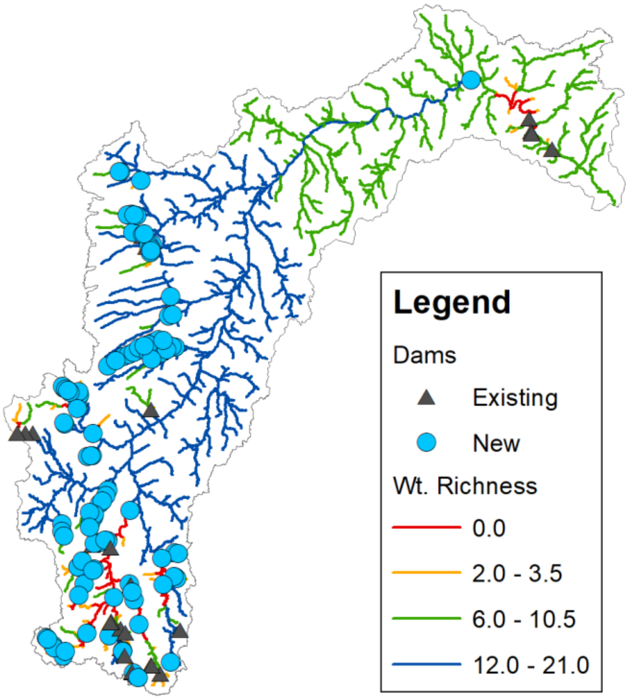
[Figure 5c]



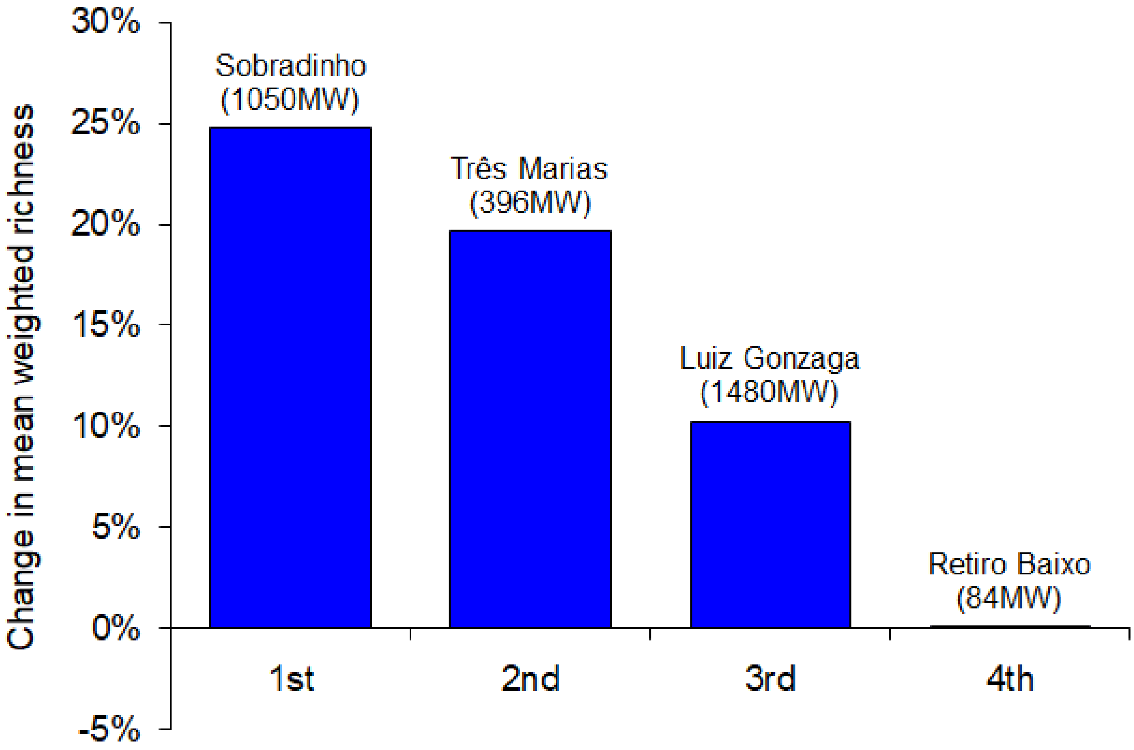
[Figure 5d]



[Figure 5e]



[Figure 6a]



[Figure 6b]