

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

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16
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21 **Abstract**

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

40 **Introduction**

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

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

58 Various barrier prioritization methods have appeared in recent years (Kemp and O’Hanley 2010).
59 These include simple but inefficient scoring-and-ranking approaches (Kocovsky *et al.* 2009),
60 spatially informed graph theoretic models (Segurado *et al.* 2013), and optimization based
61 techniques (O’Hanley and Tomberlin 2005). Applications are biased, however, to developed,
62 northern temperate regions, where the majority of viable hydropower and water storage potential

63 has already been realized. Installation of new infrastructure is rarely considered, though there are
64 exceptions (Ziv *et al.* 2012; Ioannidou and O’Hanley 2018). Existing methods also frequently
65 apply assumptions appropriate to a limited number of economically important fish taxa, usually
66 with anadromous migrations (e.g., Salmonidae). Unfortunately, such tools cannot be easily
67 transferred to tropical regions, which maintain rich fish communities with more complex life-
68 histories and movement strategies (Carolsfield *et al.* 2003; Hogan *et al.* 2004). There is an urgent
69 need to develop prioritization methods for dam installation and removal that support more
70 sustainable water and energy resource management in tropical regions.

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

82 This study describes the use of a novel spatial optimization model for locating hydropower dams
83 to balance tradeoffs between hydropower generation potential and migratory fish species richness.
84 A case study of the São Francisco River basin is used to explore various hydropower development
85 scenarios and their impacts on riverine fish biodiversity. There are at least two noteworthy aspects

86 of our model. First, whereas existing barrier optimization tools are designed exclusively for
87 migratory fish in northern latitudes (Kuby *et al.* 2005; Neeson *et al.* 2015; King *et al.* 2017), our
88 model is tailored to the unique dispersal patterns of tropical migratory fish species. Such species
89 generally require long, unimpeded stretches of free-flowing river to complete their life-cycle. To
90 model fish with this type of dispersal pattern, we introduce the concept of a river pathway. The
91 use of river pathways represents a novel way to describe river connectivity that contrasts markedly
92 from existing river connectivity metrics. Second, current models focus exclusively on
93 removal/mitigation of existing barriers (Neeson *et al.* 2015) or, in a limited number of cases, the
94 location of new dams (Ziv *et al.* 2012; Ioannidou and O’Hanley 2018). In contrast, our model
95 combines both dam placement and removal decisions. This is particularly useful for investigating
96 how hydropower offsetting could be used to achieve biodiversity gains, while maintaining or
97 expanding hydropower generation potential (Owen and Apse 2015).

98 **Methods**

99 *Study Area*

100 The São Francisco (Figure 1) is the 25th longest river in the world (Tan and Sheng 2004). The basin
101 covers 7.4% (631,133 km²) of Brazil between latitudes 7°S and 21°S (Knoppers *et al.* 2006).
102 Primary water uses include power generation, irrigation, urban/industrial water supply, navigation,
103 and fishing. Downstream of Três Marias dam, floodplains along the São Francisco occupy
104 approximately 2000km² (Welcomme 1990), supporting one of the most important inland Brazilian
105 fisheries (Sato and Godinho 2004).

106 [Figure 1 approx. here]

107 Since the 1950s, the São Francisco River has been dammed for energy generation and flow
108 regulation. Presently, there are 28 large (≥ 30 MW) hydropower dams and dam complexes

109 (hereafter dams) across the basin supplying 10.8GW of installed generation capacity. There are at
110 least 117 proposed development sites, which if built would provide an additional 3.9GW (+27%)
111 of hydropower. The vast majority of these candidate sites are concentrated in the upper reaches of
112 the basin to the west and south.

113 *Migratory Fish Species Richness and Abundance*

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

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

126 [Figure 2 approx. here]

127 We modeled richness for 12 native migratory fish species in the São Francisco as function of river
128 length (Appendix A). To do so, we introduce the concept of a river “pathway.” A pathway is the
129 longest continuous stretch of river in the direction of flow unimpeded by dams or reservoirs. A
130 pathway is uniquely identified by its terminal upstream and downstream segments, starting either

131 at the river headwaters or immediately downstream of a dam and ending either immediately above
132 the first downstream reservoir or the river mouth (Figure 1). Based on Zambaldi and Pompeu
133 (*Under review*), pathways were subdivided into three size classes and assigned species richness
134 estimates proportional to size (Table 1).

135 [Table 1 approx. here]

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

141 [Table 2 approx. here]

142 *Geospatial Data Processing*

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

148 Spatial coordinates and hydropower generation potential of all existing/proposed hydropower
149 dams were taken from the Brazilian Electricity Energy Regulatory Agency database
150 (SIGEL/ANEEL 2016). For several dam complexes sharing a common reservoir, individual dams
151 were merged into a single location and their generation potential added together. The Barrier
152 Analysis Tool (BAT) add-in for ArcGIS (Hornby 2013) was then used to snap dam locations (50m

153 snapping distance) to the river network and split the network at each dam site. After snapping, a
154 total of 28 existing and 117 proposed dam sites were identified.

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

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

165 *Hydropower Dam Optimization Model*

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

174 [Table 3 approx. here]

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

$$177 \quad x_j = \begin{cases} 1 & \text{if hydropower dam } j \text{ is present} \\ 0 & \text{otherwise} \end{cases}$$

$$178 \quad y_f = \begin{cases} 1 & \text{if pathway } f \text{ is barrier-free} \\ 0 & \text{otherwise} \end{cases}$$

$$179 \quad z_{s\ell k} = \begin{cases} 1 & \text{if segment } s \text{ is assigned to a barrier-free pathway of size class } \ell \\ & \text{and floodplain class } k \\ 0 & \text{otherwise} \end{cases}$$

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

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

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

s. t.

$$\sum_{j \in J} h_j x_j \geq \theta H' \quad (2)$$

$$\sum_{j \in J'} x_j \geq n' - m \quad (3)$$

$$x_j + x_t \leq 1 \quad \forall j \in J, t \in E_j \quad (4)$$

$$y_f + x_j \leq 1 \quad \forall f \in F, j \in B_f \quad (5)$$

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

$$\sum_{\ell \in L} \sum_{k \in K} z_{s\ell k} \leq 1 \quad \forall s \in S \quad (7)$$

$$x_j \in \{0,1\} \quad \forall j \in J \quad (8)$$

$$y_f \geq 0 \quad \forall f \in F \quad (9)$$

$$z_{s\ell k} \geq 0 \quad \forall s \in S, \ell \in L, k \in K \quad (10)$$

195 The objective (1) maximizes mean migratory fish species richness, weighted by access to
 196 floodplain areas, within the river network. This is found by summing across all segments (s),
 197 pathway size classes (ℓ), and floodplain classes (k) the richness of each pathway (R_ℓ), weighted
 198 by effective abundance (w_k) and segment size (v_s), and then dividing by total network size (V).
 199 Note that in our case study, segment and total network size are measured as order-weighted length
 200 (km), however, in other situations size could be measured as wetted area (km²) or other some other
 201 suitable metric. Constraint (2) requires total hydropower potential to be greater than or equal to
 202 some multiple $\theta \geq 0$ of current potential H' . Constraint (3) specifies that no more than m dams

203 can be removed among the n' existing dams. Given the availability of data on dam removal costs,
 204 constraint (3) could just as easily be replaced with the constraint:

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

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

208 To continue, constraints (4) prevent the nonsensical placement of dams within the “exclusion
 209 zone” of any dam site j . The exclusion zone for dam site j (E_j) includes all upstream locations that
 210 would be completely submerged (within a reservoir) or whose hydropower potential would be
 211 excessively reduced (as a result of backwater effects) due to the construction of dam j . More
 212 specifically, if dam j is present ($x_j = 1$), then no dams within its exclusion zone can be present
 213 ($x_t = 0, \forall t \in E_j$) or if a dam is present in the exclusion zone of j ($\exists t \in E_j | x_t = 1$), then dam j
 214 cannot be present ($x_j = 0$). Inequalities (5) state that pathway f can be “active” (i.e., designated
 215 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
 216 (6) stipulates that segment s can only be assigned to a pathway of size class ℓ and floodplain class
 217 k ($z_{s\ell k} = 1$) if it lies within at least one active pathway of size class ℓ and floodplain class k ($\exists f \in$
 218 $P_{s\ell k} | y_f = 1$). Inequalities (7) further require that segment s can be assigned to at most one pathway
 219 of any size and floodplain class. Finally, constraints (8) place binary restrictions on the x_j dam
 220 siting variables, while constraints (9)-(10) require variables y_f and $z_{s\ell k}$ to be non-negative. Note
 221 that due to the structure of the model, variables y_f and $z_{s\ell k}$ are guaranteed to take on binary values.

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

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

237 We further observe that our model can be viewed more generally as a multi-objective problem
238 involving the maximization of mean weighted migratory fish species richness ($\max Z_1 =$
239 $V^{-1} \sum_{s \in S} \sum_{\ell \in L} \sum_{k \in K} v_s w_k R_{\ell} z_{s\ell k}$), maximization of hydropower generation potential ($\max Z_2 =$
240 $\sum_{j \in J} h_j x_j$), and minimization of the number of dam removals ($\min Z_3 = n' - \sum_{j \in J'} x_j$). The latter
241 two objectives are incorporated as constraints in the model, as opposed to the common approach
242 of combining all three into a single weighted objective function ($\max \alpha_1 Z_1 + \alpha_2 Z_2 + \alpha_3 Z_3$, with
243 $\alpha_1, \alpha_2 \geq 0$ and $\alpha_3 \leq 0$ being the weights for objectives Z_1 , Z_2 , and Z_3 , respectively). To assess
244 tradeoffs among objectives, one can systematically vary minimum hydropower requirements (θ)

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

249 We implemented our model in the OPL modeling language using CPLEX studio version 12.7.1
250 (IBM 2017). CPLEX is a state-of-the-art commercial software package that employs branch-and-
251 cut methods to solve mixed integer linear programs (MILPs). All experiments were performed on
252 the same dual-core Lenovo ThinkPad T470 laptop (Intel i7-7600U processor, 2.8GHz per chip)
253 with 32 GB of RAM. Solution times varied from under 1 second to 6.5 minutes, which is
254 remarkable given the large size of the model, which includes 165,118 variables (145 binary) and
255 203,132 constraints.

256 **Results**

257 A range of tradeoffs exist between mean weighted species richness and hydropower generation
258 potential in the São Francisco for different numbers of dam removals (Figure 3). To structure our
259 analysis, we focus on seven selected hydropower development scenarios: 1) a pre-dam baseline in
260 which the river basin is assumed to be in a fully natural state (Baseline); 2) the current situation
261 given existing dams (Current); 3) an ideal scenario in which dam locations are optimized to achieve
262 current generation potential (Ideal); 4) removal of up to one existing dam combined with
263 optimizing the siting of new dams to compensate for lost hydropower (Offset); 5) a 20% increase
264 in generation potential assuming the fewest number of new dam sites are selected (Future A); 6) a
265 20% increase in generation potential assuming new dam sites are optimized and no existing dams
266 are removed (Future B); and 7) a 20% increase in generation potential assuming new dam sites are
267 optimized and up to one existing dam can be removed (Future C). Note that comparisons between

268 scenarios are based largely on mean weighted migratory fish richness. Weighted richness (range
269 2-21 species) accounts for the importance of floodplain access and is, therefore, generally much
270 higher than unweighted richness (range 2-12 species).

271 [Figure 3 approx. here]

272 It is clear that hydropower development in the São Francisco has detrimentally impacted fish
273 biodiversity. Weighted richness has been reduced by 51% (from 20.2 species to 9.9 species)
274 compared to a pre-dam baseline (Current versus Baseline, Figure 3). Had dam sites been optimized
275 from the start, average weighted species richness would be 63% higher (+6.2 species) relative to
276 the current value (Ideal, Figure 4a). If one dam can be removed while ensuring hydropower
277 potential is offset by the optimal siting of new dams, then weighted richness could increase 25%
278 (+2.4 species) above the current average (Offset, Figure 4a).

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

287 [Figure 4 approx. here]

288 A more in-depth analysis of the results reveals two key insights. The first is that building many
289 small and medium megawatt dams in the upper reaches of the basin would yield substantially

290 better biodiversity outcomes than building a few large megawatt dams along the São Francisco
291 River or its main tributaries. The Offset scenario, for example, achieves higher fish richness
292 compared to the Current scenario by removing one very large dam situated on the main stem (the
293 1005MW Sobradinho dam) and replacing it with 35 smaller dams (mean 30MW) located mainly
294 on minor tributaries (Figure 5b). Similarly, optimized solutions Future B and Future C, which both
295 produce higher richness compared to non-optimized solution Future A, recommend siting around
296 12 times the number of new dams as Future A (107-109 versus 9, Figure 4b), with average
297 hydropower per new dam around a tenth (20-29MW versus 240MW). For Future B, no new dams
298 are located on the main stem below Três Marias (Figure 5d). For Future C, only two new dams are
299 found along the main stem below Três Marias (Figure 5e) – one in the lower part of the basin
300 below the Sobradinho, the other a short distance downstream from the Três Marias. Future A, in
301 contrast, locates four dams on the main stem and all but one of the five other dams near the
302 confluences of major tributaries (Figure 5c). Intuitively, the siting pattern for optimized solutions
303 makes sense. Species richness losses for optimized solutions tend to be localized in low-order
304 tributaries, while access to floodplains, which is mostly found along high-order channels, is
305 maintained.

306 [Figure 5 approx. here]

307 A second key insight is that even limited dam removal has the potential to significantly enhance
308 fish biodiversity. The Offset and Future C scenarios both produce a significant increase in fish
309 richness (19-25%) with removal of a single dam. These scenarios are not unique in this regard,
310 however. The curve for weighted richness versus hydropower potential given ≤ 1 dam removal is
311 near optimal (i.e., almost overlaps the ≤ 28 dam removal curve) for a 15% increase in hydropower
312 or higher, while the curve given ≤ 2 dam removals is near optimal for current levels of hydropower

313 or higher (Figure 3). What this indicates is that removing just 1-2 dams could return the São
314 Francisco to a near optimal state depending on hydropower requirements.

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

322 [Figure 6 approx. here]

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

335 hydropower potential. As recently as 2016, reservoir volume of the Três Marias was only at 38%
336 of capacity at the end of wet season (BHAZ 2016).

337 **Discussion**

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

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

350 In point of fact, features of our model make it well suited for informing efficient hydropower
351 development across the wider tropics and subtropics (e.g., the Amazon, Mekong, equatorial
352 Africa), where the vast majority of hydropower dam building expected to be concentrated in the
353 coming years (Grill *et al.* 2015; Winemiller *et al.* 2016). Unlike existing barrier optimization
354 approaches, our model is specifically designed to accommodate the life-cycle patterns common to
355 tropical migratory fish species (i.e., pelagic-broadcast spawners). More importantly, the model is
356 data light – only basic biological information (i.e., estimates of species richness as a function of
357 river length and floodplain size class multipliers) and easy-to-obtain geospatial data (i.e., river

358 network, floodplain area, dam location, and reservoir area data) are required. This is a key
359 advantage as developing countries are often hindered by a lack of high quality data, especially
360 detailed biological information (Groves *et al.* 2002).

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

370 It is worth mentioning at least four simplifications of our study. First, due to a lack of catchment-
371 wide data regarding fish species endemism, we had no choice but to treat equally sized sections of
372 river with equal floodplain access as fungible. Given species distribution data, a more targeted
373 approach to conservation could be adopted that limits losses for species of conservation concern.
374 Second, we did not consider the potential effects of dams on flow regulation. Consequently, our
375 model likely underestimates reductions in weighted fish richness due to the reduction of floodplain
376 areas (Nestler *et al.* 2012). Third, our model does not take into account the importance of how
377 different habitat types are spatially distributed. Separation of spawning and rearing grounds by
378 dams and reservoirs can create source-sink dynamics (Godinho and Kynard 2009) and ecological
379 traps (Pelicice and Agostinho 2008). Incorporating additional autecology and spatial information
380 could reduce the risk posed by confining fish populations within short reaches lacking the full

381 range of critical habitats. Fourth, an interesting modification to our model would be to relax the
382 assumption that dams form total barriers to fish dispersal. For example, reservoirs below critical
383 size thresholds (Pelicice *et al.* 2015) should permit at least a fraction of embryos/larvae to move
384 and potentially supplement richness downstream, whereas fish passes with even limited
385 effectiveness might enable sufficient numbers of adults to pass small dams and access upstream
386 spawning areas. More realistic modeling of fish dispersal could help to identify better opportunities
387 for locating, removing, or mitigating dams that maximize fish biodiversity.

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522 **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

523

524

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

526 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

527

528 **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' = J' $
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

530 **Figure Captions**

531

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

533

534 **Figure 2.** Example river network with dams shown as small lettered rectangles. Dams A and B are
535 existing structures (solid lines), dam C is a proposed structure (dashed lines). Blue shaded areas
536 above each dam depict reservoirs (solid lines for existing, dashed lines for proposed). The river
537 network is split into a total of 16 river segments (numbered 1 to 16) based on confluence and
538 reservoir bounding points. All four possible pathway types are shown (dashed orange curves).
539 Starting/ending segments 16 and 1 form a “terminus-to-mouth” pathway (denoted 16→1), 11→5
540 is a “terminus-to-above reservoir” pathway, 2→1 is a “below dam-to-mouth” pathway, and 6→5
541 is a “below dam-to-above reservoir” pathway. If dam C were installed, then pathway 11→5 would
542 be split into two new pathways 11→11 and 9→5. If dam B were removed, then pathways 8→8 and
543 6→5 would be replaced by a new pathway 8→5.

544

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

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

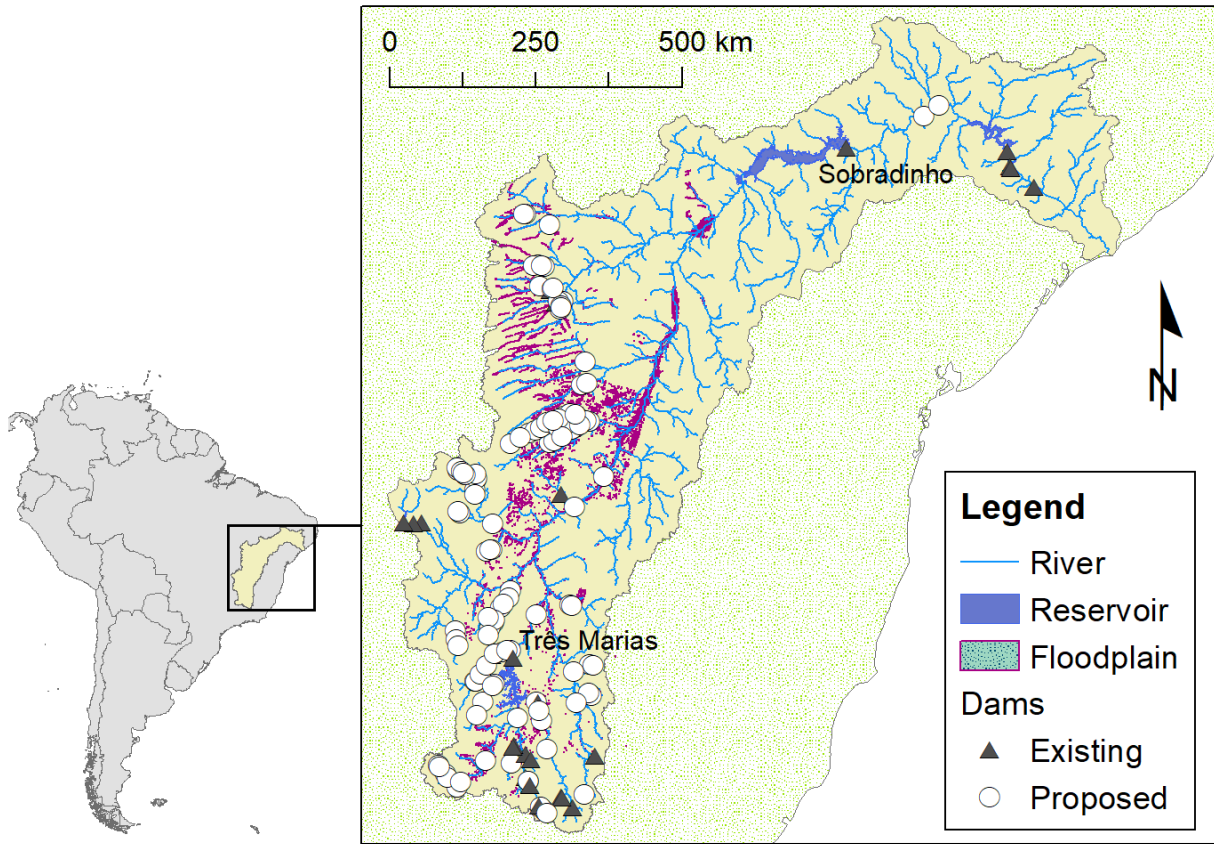
555

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

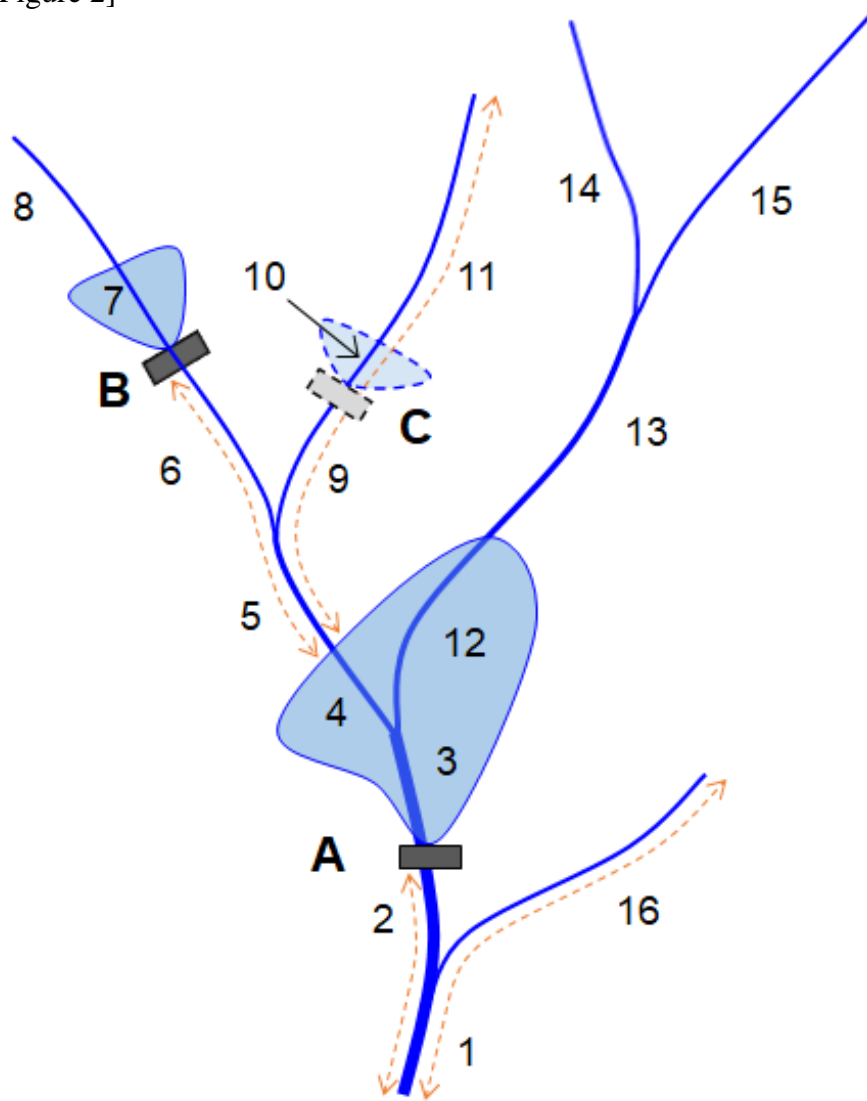
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560 **Figure 6.** Percent change in mean weighted migratory fish species richness relative to current for
561 the first to fourth best optimal solutions given a 0% increase (a) or 20% increase (b) in hydropower
562 generation potential and up to one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

567

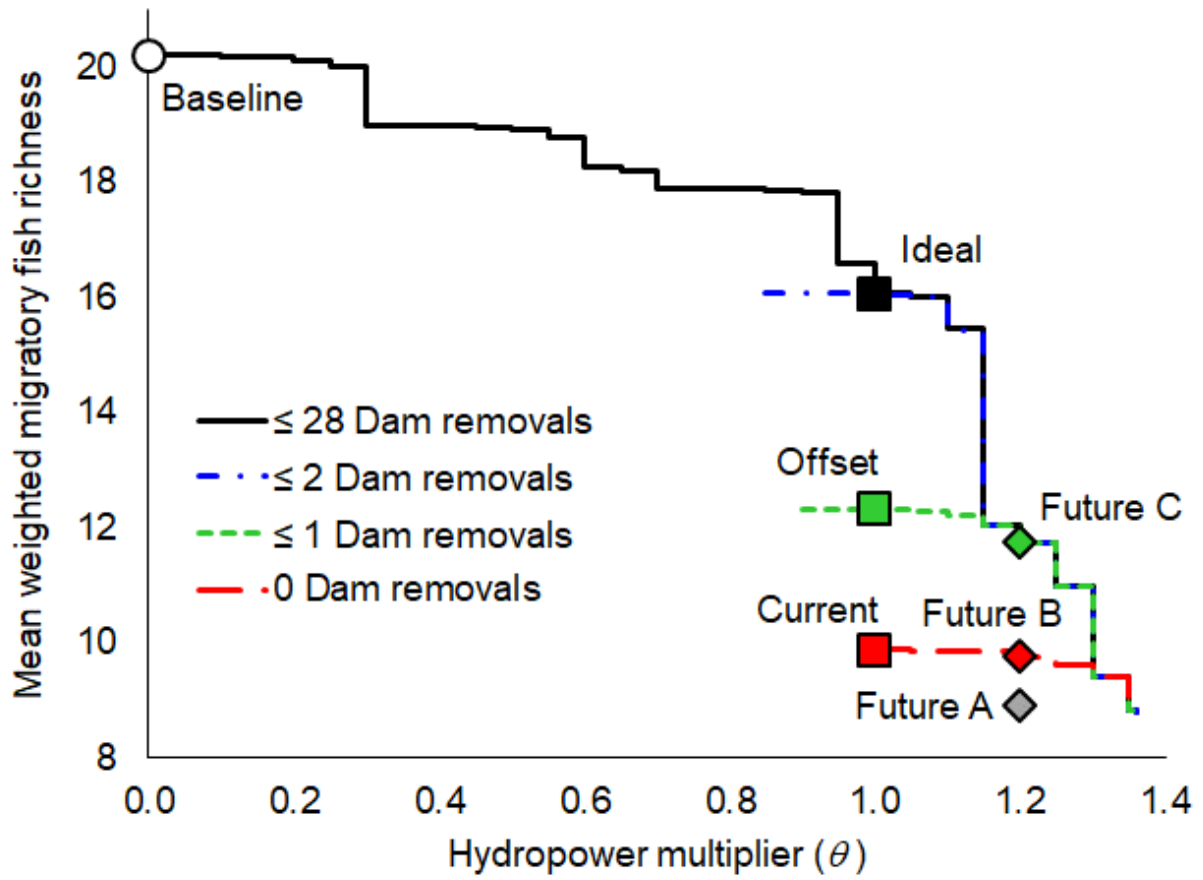


570 [Figure 2]



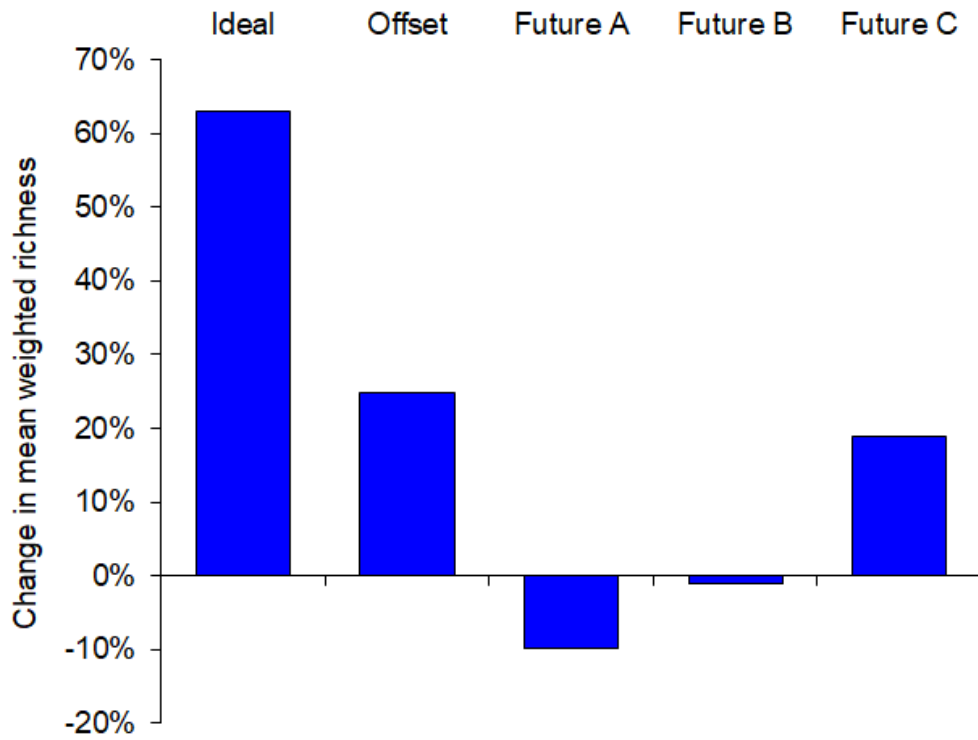
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572 [Figure 3]



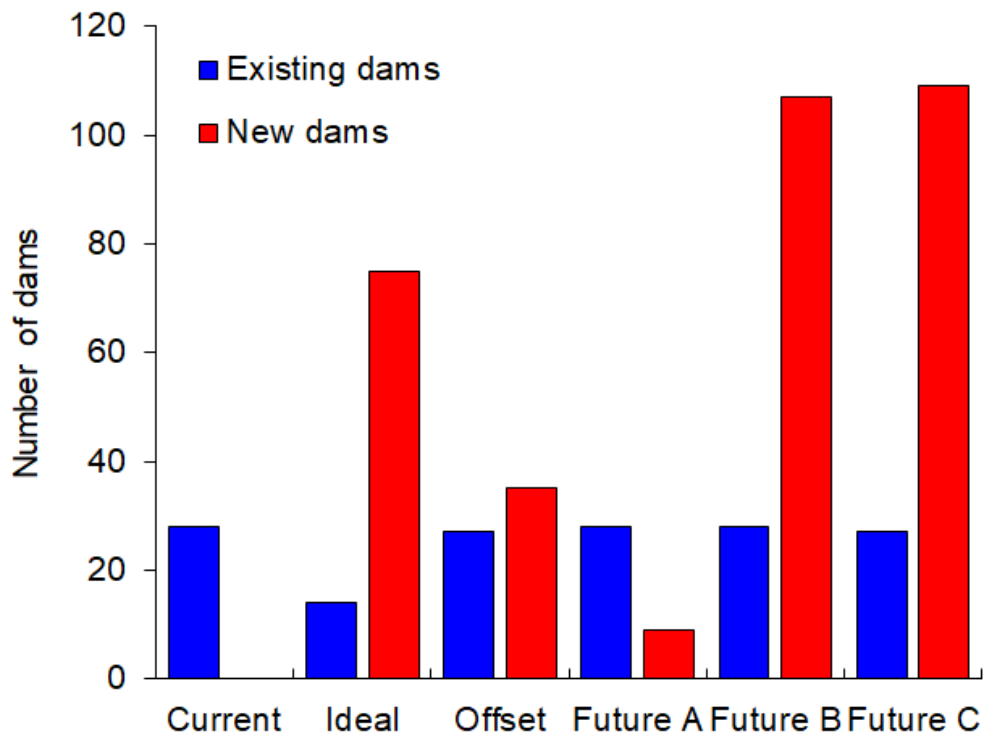
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574 [Figure 4a]



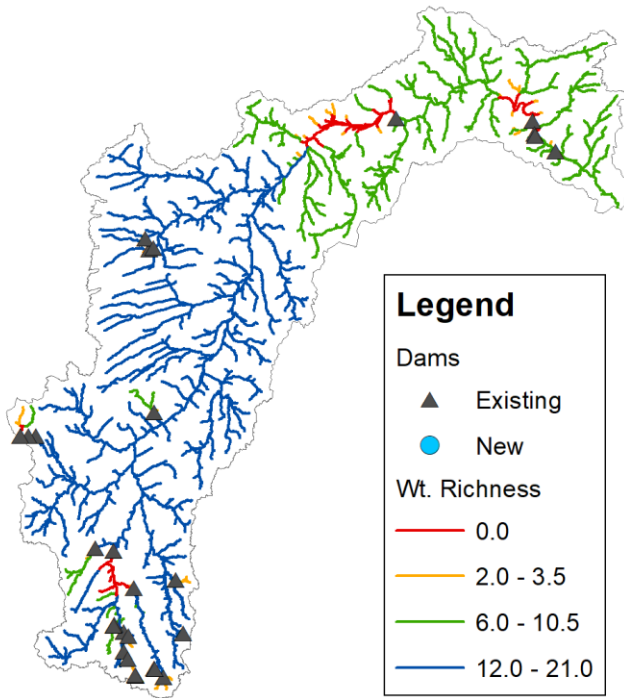
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576 [Figure 4b]



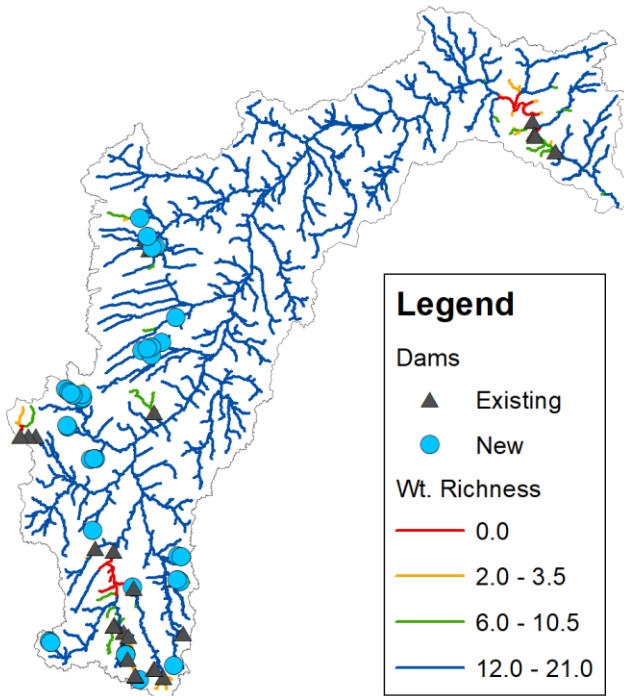
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578 [Figure 5a]



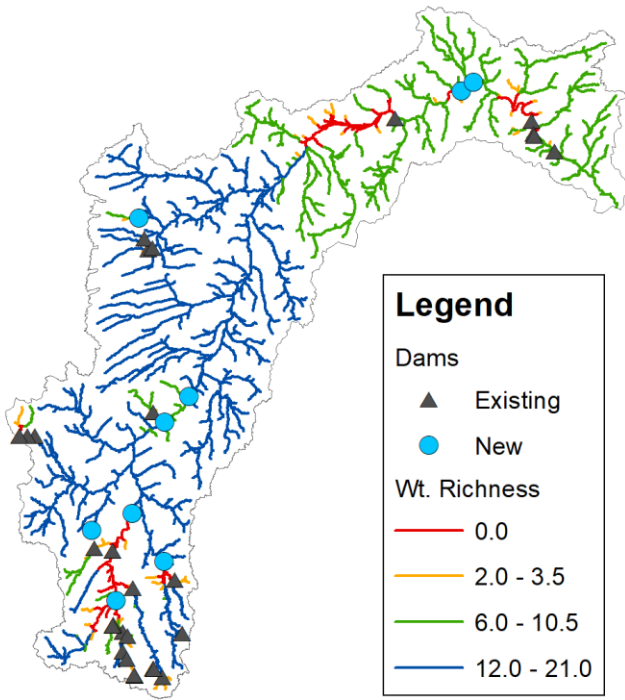
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580 [Figure 5b]



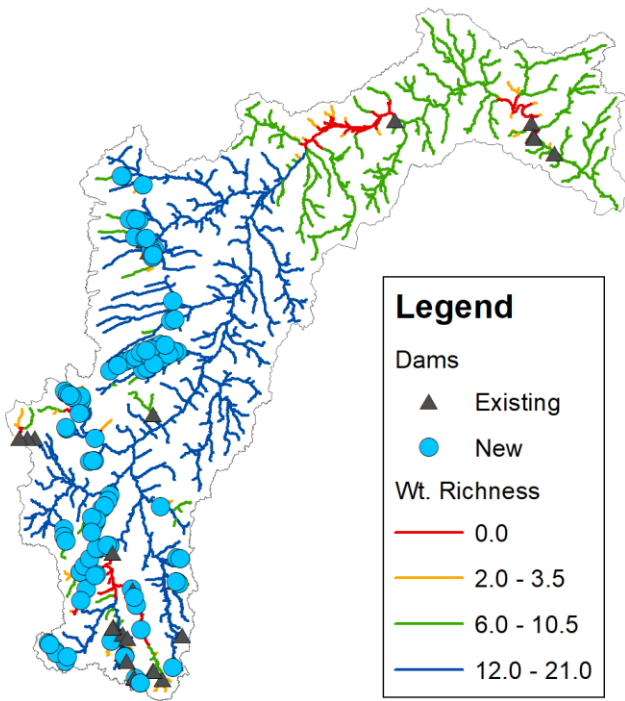
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582 [Figure 5c]



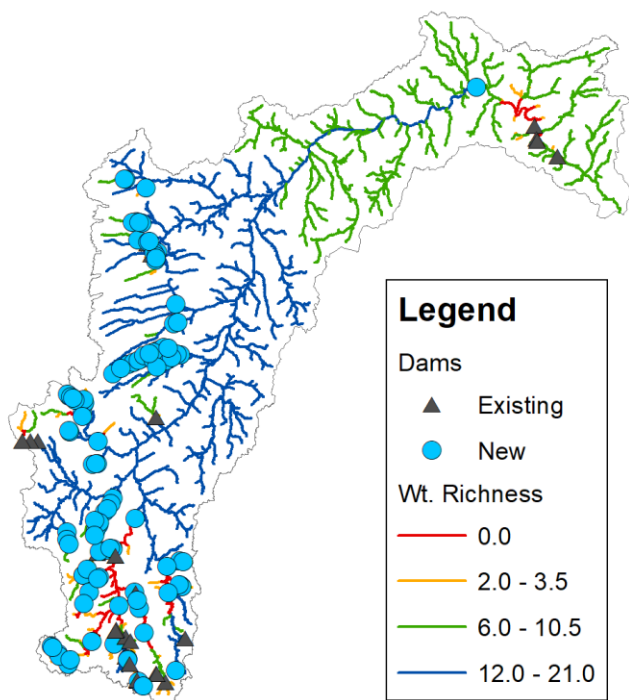
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584 [Figure 5d]



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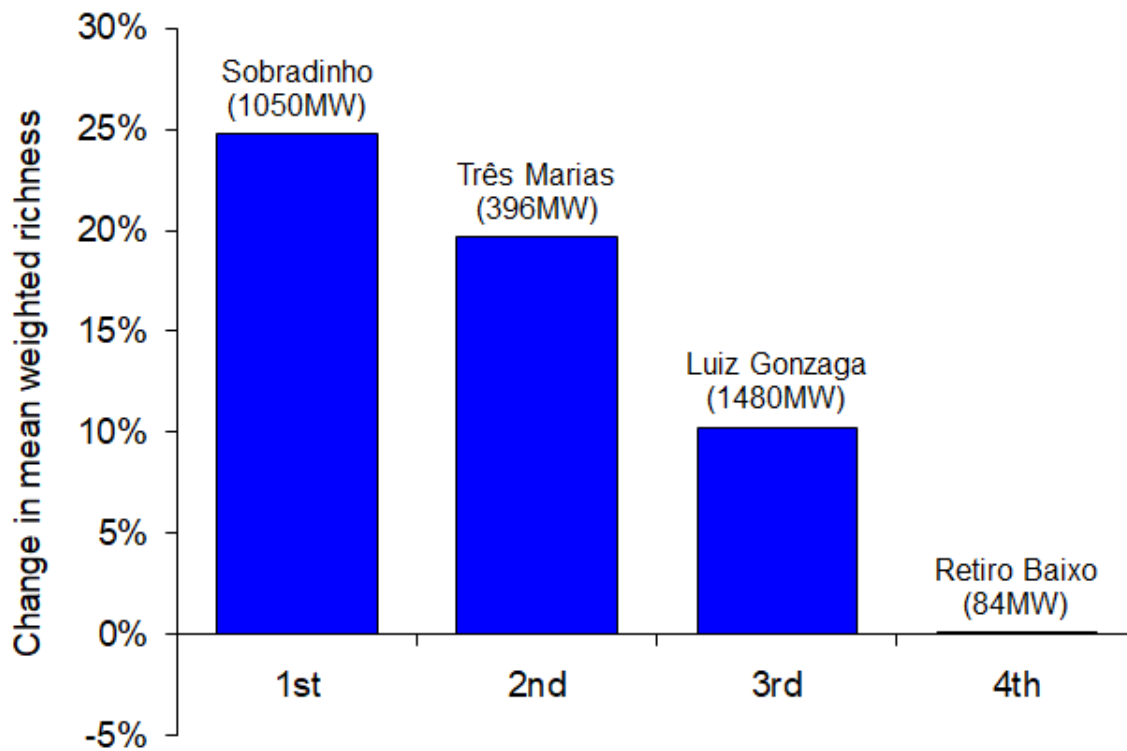
586 [Figure 5e]



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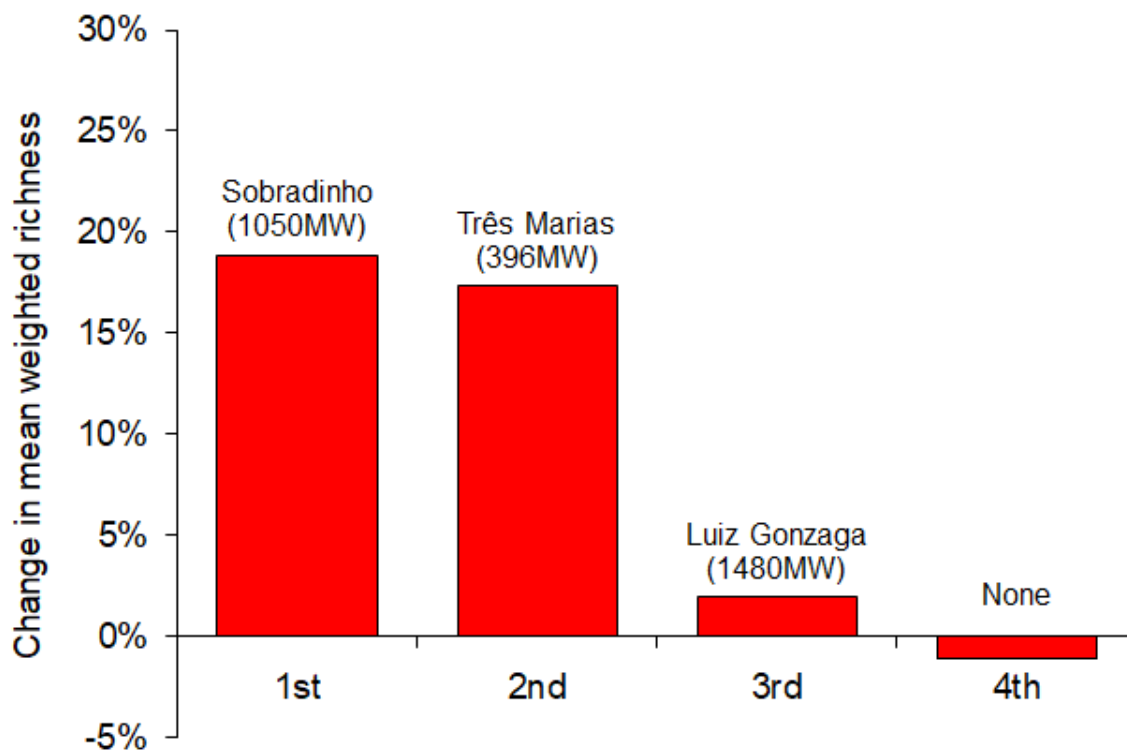
588

589 [Figure 6a]



590

591 [Figure 6b]



592