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Strategic methodology to set priorities for sustainable hydropower development in a biodiversity hotspot

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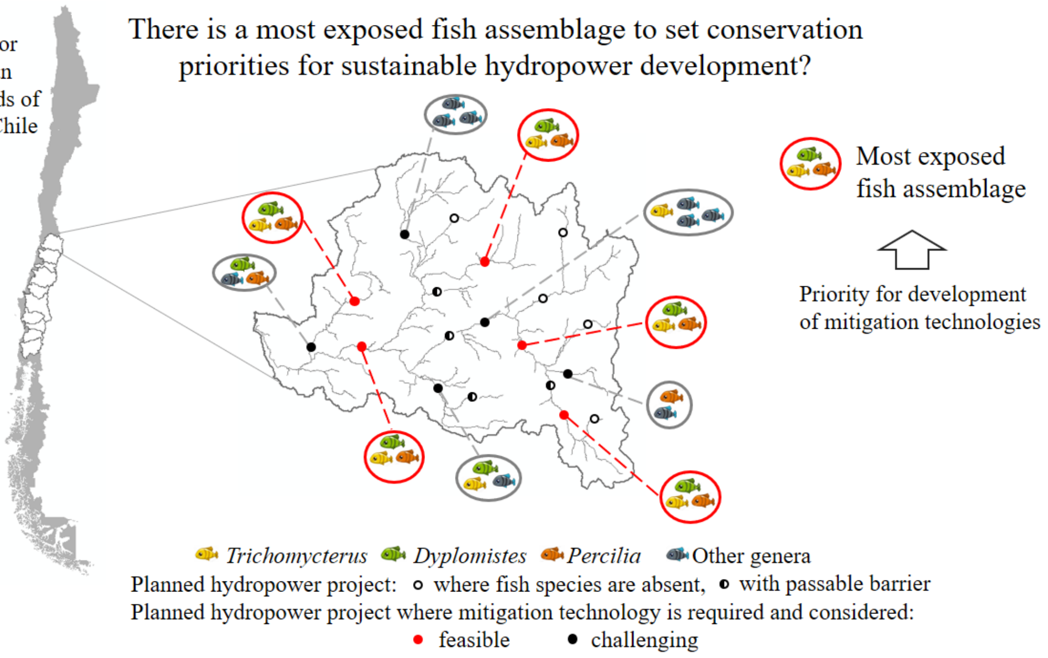
GRAPHICAL ABSTRACT



ABSTRACT

Massive exploitation of freshwater systems for hydropower generation in developing countries is challenging sustainability due to cumulative environmental impacts in regions with high endemism. Habitat fragmentation is recognized as a major impact on river ecosystems. The nature and magnitude of connectivity loss depend on characteristics of the hydropower projects, and of the threatened fish communities. In areas where appropriate mitigation technology is lacking, there is a need to identify the fish species that are most at risk to better concentrate efforts. This paper aimed to set conservation priorities for sustainable hydropower development by analyzing native fish species and project characteristics. The Chilean ichthyogeographic province, an ecoregion with high endemism and massive hydropower projects development, has been considered as a case study. By using overlapping information on the characteristics of 1124 hydropower projects and distribution of native fish species, we identified three project categories of projects based on their need for mitigation. These were projects where mitigation was considered: a) not required (15%), b) required and feasible (35%), and c) required but challenging (50%). Projects where mitigation was not required were located at sites where native fish were absent and/or where water intakes allowed fish to pass. Interestingly, projects where mitigation was feasible were inhabited by a species assemblage that comprised the genus *Trichomycterus*, *Diplomystes* and *Percilia*, and the species *Ch. pisciculus* and *B. maldonadoi*. This finding emphasises the need to develop a multispecific fishway that can accommodate this group. Projects where mitigation would be difficult to achieve were located at sites with a variety of different assemblages, thus making a standard fish pass solution challenging and site-specific. This study advances understanding for the need to develop mitigation strategies and technologies in ecoregions of high endemism threatened by hydropower and to prioritize the construction of planned projects.

Keywords: Dams, native fish, conservation, mitigation, fish passage, Chile.

1. Introduction

Worldwide, urgent reduction of greenhouse gases due to climate change motivates the development of non-conventional renewable energies to satisfy increasing energy demand. Globally, hydropower is the leading renewable energy source accounting for 18% of total electricity supply (Kumar *et al.*, 2011), and its development has experienced a recent boom with small and medium-sized dams (1–100 MW) dominating in number (>75 %) (Zarfl *et al.* 2015). The global installed capacity of small hydropower projects (SHP, i.e. installed capacity less than 20 MW) is estimated to be 75 GW, with an additional 173 GW of potential remaining to be developed (SHW, 2013). At the same time, hydropower can severely impact freshwater ecosystems (Zhou *et al.*, 2015 Lees *et al.*, 2016, Winemiller *et al.* 2016, Latrubesse *et al.* 2017).

River fragmentation arguably has had the most profound ecological effects and has been considered the greatest threat to riverine biodiversity (Vörösmarty *et al.*, 2010), and primary cause for the decline of freshwater ichthyofauna (Romao, 2017). Barriers to migration can restrict access to critical habitats required for foraging and feeding, predator avoidance, shelter, and spawning (Gibson *et al.*, 2005), and ultimately lead to a reduction in recruitment, population decline, and a loss of biodiversity (Franklin and Bartels, 2012). There are many examples of decline, and occasional extinction of the fish population when rivers are dammed (e.g., Jelks *et al*., 2008; Vörösmarty *et al.*, 2010; Radinger and Wolter, 2014). Negative effects, such as disruption of gene flow (e.g., Frankham, 2015; Valenzuela et al., 2019); physical habitat disturbance (e.g., Howell, 2006); and local extinction due to stochastic demographic processes (e.g., Stephens and Sutherland, 1999), have not been confined only to migratory fish, but also resident species (Wilkes *et al.*, 2018). The majority of Chilean native fish species are resident and do not undertake extensive migration between clearly separated critical habitats, yet the movement of individuals and the genetic information they carry is critically important for population viability (Wilkes *et al.*, 2018). This was recently acknowledging for *Percilia irwini*, endemic Chilean species (Valenzuela *et al.*, 2019). Fishes have been threatened on all continents, with nearly 50% of freshwater ecoregions (397 assessed) obstructed by large- and medium-sized dams (Liermann *et al.*, 2012).

The nature and magnitude of connectivity loss depends on the characteristics of the hydropower projects and the impacted ecosystem. Although the precise design of hydropower projects depends on site conditions, SHP typically diverts flow in the order of a few cubic meters per second (< 100 m^3/s), and bottom intakes such as *tyrolean* weirs, or lateral intakes are typically used. The small dams associated with these intakes, commonly varying between 2 and 20 m height, can severely fragment habitat (Link and Habit, 2015). Furthermore, the magnitude of impacts on the aquatic biota depends on diversity, sensitivity, resistance and resilience status (Ziv *et al.*, 2012; McCluney *et al.*, 2014). Sites inhabited by fish communities composed of endemic and/or vulnerable species are at greatest risk, and if developed impacts must be mitigated.

In an attempt to counteract the negative effects of habitat fragmentation, a wide variety of devices have been installed at river barriers to restore connectivity, with fishways being the most common, enabling fish to bypass the impediment under their own effort (Clay, 1995). Current fish pass design is based on a traditional focus on only one or a few species, often salmonids in northern temperate regions, and thus they may not be effective in other regions, such as in the southern hemisphere (Link and Habit, 2015; Kemp, 2016; Franklin and Baker, 2016). The application of traditional fish passage solutions to other geographical regions has been challenging for many reasons, largely related to differences in species richness and abundance, diversity of life histories, body morphologies, swimming capabilities and behaviours when compared to the target species for which they were designed (Kemp, 2016). Over the last decade, this bias has been recognized and now efforts have been made to develop fish passage for a wider range of target species (Santos *et al.*, 2014; Branco *et al.*, 2017; Romao *et al.*, 2018).

To develop an effective mitigation technology in ecoregions with high endemism there is a need to select the most appropriated group of target species to prioritize conservation efforts. Meffe and Berra (1988) introduced the concept of a selecting core group of species related to their presence, abundance, i.e. persistence and stability of the assemblage. For species conservation, though, the use of surrogate species is the most commonly applied strategy (Thornton *et al.*, 2016). Species surrogate is a blanket term that encompasses several different concepts including indicator species, umbrella species, key-stone species, and flagship species, among others (Fleishman *et al.*, 2000; Caro, 2010; Thornthon *et al.*, 2016). In the case of developing mitigation technologies to restore longitudinal habitat connectivity, such as fishways, the core group concept by Meffe and Berra (1988) seems to be the best available approach to identify the species most exposed to the impacts of hydropower plants, allowing a massive technological solution.

This study aimed to develop a methodology to set conservation priorities for sustainable hydropower development in Chile by analyzing the characteristics of Chilean native species and planned hydropower projects. This region is generating considerable attention for hydropower exploitation, as it comprises 10 high gradient watersheds with an estimated 12.5 GW potential (Ministry of Energy, 2015), most of which will be supplied by SHP. At the same time, central Chile is part of the Chilean ichthyogeographic province (*sensu* Dyer 2000), a hotspot of biodiversity (Myers *et al.* 2000), accommodating a unique and highly endemic fish fauna. Thus, a major concern is the potential fragmentation of the whole region and the cumulative effects of multiple projects built within the natural range of native species that are predominantly resident (Díaz *et al.*, 2019). Currently, none of the planned projects has been designed with any mitigation technology. The Chilean situation represents a complex environmental conflict that is common worldwide, namely, how to develop hydropower potential sustainably while conserving native species. Considering central Chile as a case study, the first objective was to develop a database for the distribution of native fish species in these watersheds. The second objective was to identify hydropower projects where fish populations would likely be impacted and superimpose this on the information maintained fish database. This would enable identification of projects according to the need for mitigation for habitat fragmentation, based on the magnitude of the impact and feasibility of applying appropriate technology. Hydropower projects were classified by sites where mitigation is: (1) not required, (2) required and considered feasible, and (3) required but considered challenging. The characteristics of the project groups and presence of fish were analyzed.

2. Methodology

2.1 Strategic methodology to set priorities for sustainable hydropower development

The planned hydropower projects were grouped into projects: a) where fish are absent due to their location, as native fishes are absent at altitudes above 1500 m.s.l. (Vila *et al.*, 1999); b) with passable barriers when the water intake does not block or partially block the channel cross-section, i.e. lateral water intakes without dam; c) with fish data, and d) without fish data.

For the project groups with fish data and impassable barriers, present species at each site were identified as a "fish assemblage", including cases where only a single species was recorded. Thus, a functional selection criterion was applied based on habitat use (Meffe and Berra, 1988). Species composition and most frequent genera of fish assemblages at each project were identified. As the swimming capabilities of Chilean native species is not well known (Laborde *et al.*, 2016), the potential fishway passage performance was estimated based on position typically held in the water column (i.e., benthic or pelagic; Kapitzke *et al.*, 2010), body size (i.e., less or more than 15 cm when adults; Katopodis and Gervais, 2012), and swimming mode (i.e., angulliform, subcarangiform, carangiform; Sfakiotakis *et al.*, 1999; Breder, 1926; Lacey *et al.*, 2012; Link and Habit, 2015). Assemblages composed of the most frequent genera and species with similar fish passage performance were considered to be the target group, to set bounded requirements for future developments of mitigation technologies. The similarity in body size is related to similar swimming capabilities (e.g., Sanz-Ronda *et al.*, 2015). The similarity in position on the water column will allow setting the location of obstacles for energy dissipation. The similarity in the swimming mode is related to fish behavior, specifically, to how fish faces obstacles (surpassing, for above; dodging, by the side; among others). The presence of a target group promotes the implementation of a mitigation technology since it involves a generalized solution, a unique design with extensive application. Only Chilean native fish species impacted by hydropower projects are included.

Generalization of results obtained for the project groups with impassable barriers and fish data, to those projects with impassable barriers without fish data, was analyzed based on statistical differences between both groups considering geographical unit, watershed and Strahler's order, capacity, dam height, turbine, and intake type, applying ANOSIM test on a Euclidean distance resemblance matrix on normalized variables. The results obtained are used to estimate the magnitude of the environmental conflict in the study area, assuming assemblages present in project groups with impassable barriers and that fish data will occur in a similar manner at projects with impassable barriers without fish data.

Statistical differences between projects where mitigation is not required, required and considered feasible, and required but considered challenging were determined to define which hydropower characteristics (i.e., geographical unit, watershed, Strahler's order, capacity, dam height, turbine, and intake type) contribute most to the differences among these three categories, applying a SIMPER routine (Warwick and Clarke, 1998). SIMPER performs pairwise comparisons of groups of sampling units and finds the average contributions of each projects to the average overall Bray-Curtis dissimilarity. All statistical analyses were performed using Primer-E (v.7.15; Clarke and Gorley, 2015). Results were considered significant if $p \leq 0.005$, and marginally significant if $0.05 < p \leq 0.07$.

2.1. Study area

The study focused on the 10 major Andean watersheds of Central Chile (between 32° and 41° Lat. S), from the Maipo River in the North to the Bueno River in the South. Approximately 90% of the area is drained by rivers flowing predominantly from East to West with a total length of approximately 200 - 400 km, Strahler's orders up to eight, and annual mean discharges at the mouth of between 100 and 1000 m^3/s. All fluvial systems follow the same pattern, flowing from the Andes to the Coast (with river longitudinal slopes in the Andes between 5-10%) through the Central Valley (Link and Habit, 2015).

The exploitable hydropower in the study area was estimated to be 12,338 GW distributed across 1124 sites (Ministry of Energy, 2015). Location (intake and outlet), capacity, head, and discharge of planned hydropower projects were obtained from the Ministry of Energy (2015) (Figure 1). Geographical units (Andean mountain range, Central valley, and Costal chain of hills), drainage networks and their properties, such as river length, Strahler's order, and elevation, were computed using GIS software (ArcGIS 10.3) from SRTM satellite images. Characteristics of the stretch of the river where planned projects are located, such as the number of channels, channel width, and longitudinal profile type (e.g., straight or curve) were estimated using Google Earth Pro.

Historical data provided by the Ministry of Environment (2015) of the presence/absence of native fish species collected at sampling sites (included over 3,500 records) in the study area was used to calculate distribution and species richness for each river network (Figure 1).

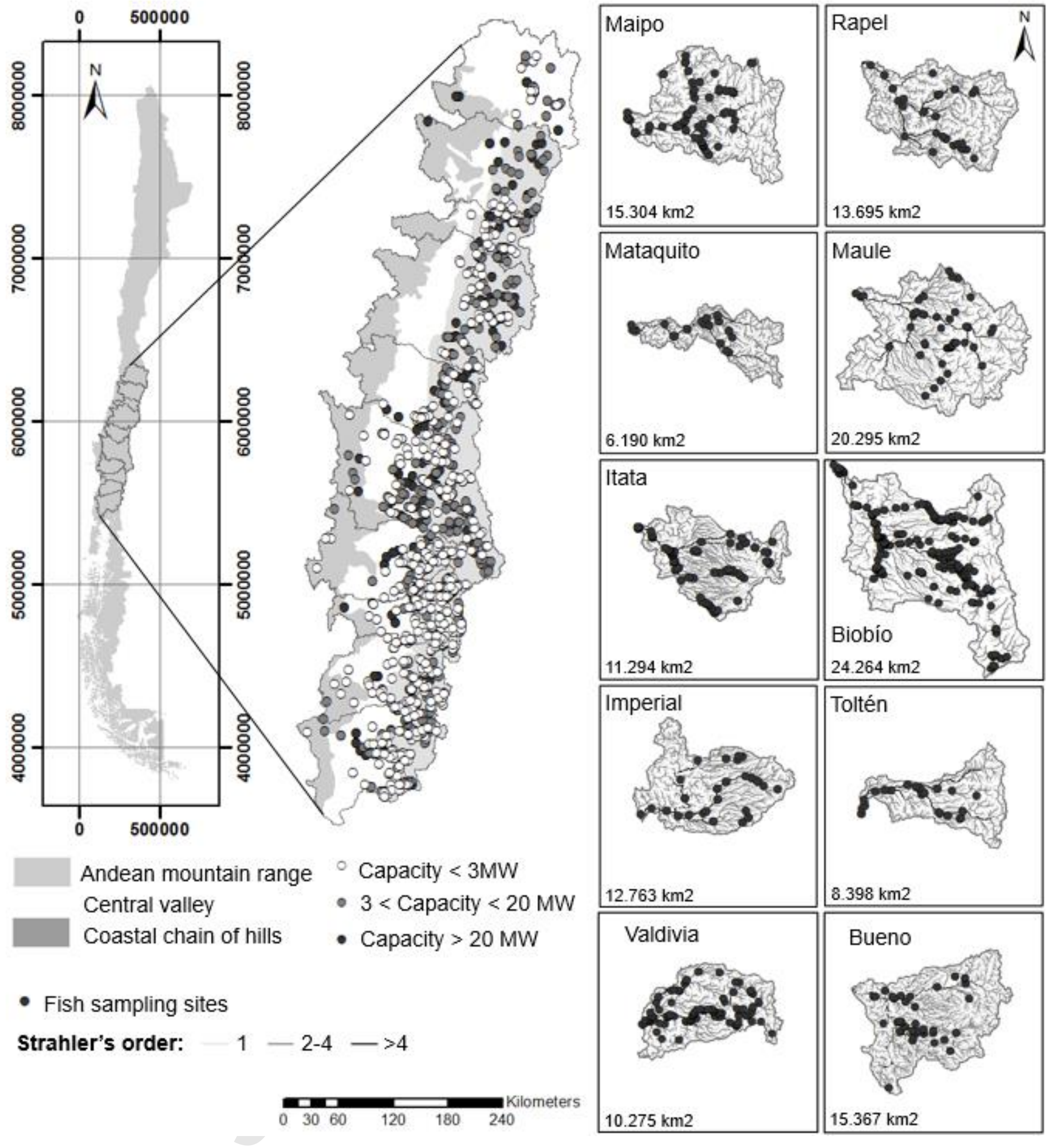


Fig. 1. Location of the study area in Chile (a), planned hydropower projects along the 10 river watersheds (b), and fish sampling sites within each of the river watersheds from North to South (c).

2.2 Species distribution, species richness and conservation status

Fish distribution was determined by interpolation of the species presence between sampling sites, considering habitat use and life history (Habit *et al.* 2005, 2006; García *et al.* 2012). Conservation status was obtained from MMA (2018). Endemism to the Chilean territory and the study area was obtained from Habit *et al.* (2006) and Vila and Habit (2015).

2.3 Hydropower projects

Hydropower projects were classified according to their geographical unit (distinguishing sites in the Andes, Central Valley and Coastal chain of hills), Strahler's order, capacity (installed capacity, C, in MW), dam height (m), turbine and intake type. Dam height was estimated based on project capacity and the distance between the intake and outlet, L (m). Two classes of dam height, h, were distinguished according to their relevance for habitat fragmentation:

$h < 20$ m if:

a) $C < 20$ MW
b) $C < 50$ MW and $L > 500$ m

and $h > 20$ m if:

a) $C > 50$ MW and $L \leq 200$ m
b) $C \geq 150$ MW and $500 \text{ m} \leq L \leq 15000$ m

The turbine type (Pelton, Francis, and Kaplan) was determined from a standard turbine selection chart according to available discharge and head. Intake type (Lateral intake with barrier, i.e. dams with weir or gate; Tyrolean intake, i.e. bottom intake; and Lateral intake without a barrier) was estimated based on characteristics of the stretch of the river: number of channels on the reach, N, channel width, W (m), longitudinal profile type, P, e.g. straight or curve.

Lateral intake with barrier if:

a) $N > 1$

b) $N = 1$ and $W > 15$ m and P = straight

c) $N = 1$ and $W \leq 5$ m and P = curve

Tyrolean intake if:

a) $N = 1$ and $W \leq 15$ m and P = straight

and Lateral intake without a barrier if:

a) $N = 1$ and $W > 5$ m and P = curve

3. Results

3.1. Species distribution, species richness and conservation status

The study area hosts 31 (65.9%) of the 47 Chilean freshwater fish species (Table 1), all are resident. These species belong to 7 families and comprise 16 genera, of which 14 are Teleosts and 2 are Agnatha (lamprey). Of all the species present in the study area, 35.4% are smaller than 15 cm total length (TL) when adult and only 19.4% reach adult sizes >25 cm TL. The most abundant groups are the Siluriforms (9 species) and Osmeriforms (7 species). Other groups represented in the study area are Characiforms (4 species), Atheriniforms (4 species), Perciforms (4 species), Petromyzontiforms (2 species) and Mugiliforms (1 species). 74.2% of the fish species are endemic to the study area, 38.7% and 48.3% are classified as Endangered and Vulnerable, respectively (Table 1). Biobío and Valdivia river basins showed the highest species richness (17 species each). The Biobío basin also contains two endemic species, namely: *Trichomycterus chiltoni* and *Percilia irwini*. Species more widespread within the study area were *Trichomycterus* *areolatus*, *Basilichthys microlepidotus*, *Percilia gillissi*, *Percichthys trucha*, and *Galaxias maculatus* (with more than 2000 km. of distribution length each).

Table 1.

Characteristics of the native fish species present in the study area. Species distribution length represent the total length of presence within all river basins inhabited. River basin names in bold correspond to basins where the species were exposed to at least one hydropower project.

				Endemic to		
Order	**Species**	**Species distribution length (km)**	**Consevation status**	**Chilean territory**	**Study area**	**River basin with presence of the species**
Characiformes	*Cheirodon kiliani*	38.1	Endangered	Yes	Yes	Valdivia
Siluriformes	*Diplomystes chilensis*	11.5	Endangered	Yes	Yes	Maipo
Osmeriformes	*Brachygalaxias gothei*	7.96	Vulnerable	Yes	Yes	Maule
Mugiliformes	*Mugil cephalus*	95.1	Less concern	No		Maipo, Mataquito, Itata, Biobío
Osmeriformes	*Aplochiton marinus*	26.4	Endangered	No		Valdivia
Atheriniformes	*Odontesthes brevianalis*	23.4	Vulnerable	Yes	No	Maipo
Atheriniformes	*Odontesthes itatanum*	9.93	Vulnerable	Yes	Yes	Itata
Characiformes	*Cheirodon pisciculus*	685.7	Vulnerable	Yes	No	**Maipo, Rapel, Mataquito**
Siluriformes	*Hatcheria*	75.8	Vulnerable	No		Imperial, **Valdivia,**

	macraei					**Bueno**
Siluriformes	*Diplomystes camposensis*	273.4	Endangered	Yes	Yes	**Valdivia,** Toltén
Osmeriformes	*Brachygalaxias bullocki*	392.3	Vulnerable	Yes	No	**Itata,** Biobío, **Imperial, Valdivia,** Toltén, **Bueno**
Petromy-zontiformes	*Mordacia lapicida*	641.6	Endangered	Yes	No	Itata, **Biobío, Toltén, Valdivia**
Siluriformes	*Trichomycterus chiltoni*	172.5	Endangered	Yes	Yes	**Biobío**
Characiformes	*Cheirodon australe*	514	Vulnerable	Yes	Yes	**Bueno, Toltén, Valdivia**
Siluriformes	*Nematogenys inermis*	256.3	Vulnerable	Yes	Yes	Maipo, **Rapel, Maule,** Itata, **Biobío**, Imperial
Osmeriformes	*Aplochiton zebra*	247.1	Endangered	Yes	No	**Bíobío, Valdivia,** Toltén, **Bueno**
Perciformes	*Percichthys melanops*	372.6	Vulnerable	Yes	Yes	**Maipo,** Mataquito, Maule, Itata, **Biobío, Toltén**
Osmeriformes	*Aplochiton taeniatus*	227.7	Endangered	No		**Toltén, Valdivia,** Bueno
Osmeriformes	*Galaxias platei*	381.4	Less concern	No		**Valdivia,** Toltén, **Bueno**
Characiformes	*Cheirodon galusdae*	1494.2	Vulnerable	Yes	Yes	Mataquito, **Maule, Itata, Biobío, Imperial**
Atheriniformes	*Odontesthes mauleanum*	914.6	Vulnerable	Yes	No	Rapel, Mataquito, Maule, Itata, **Biobío,** Imperial, **Toltén, Valdivia, Bueno**

Siluriform	*Bullockia madonadoi*	907.7	Endangered	Yes	Yes	**Itata, Biobío, Imperial, Toltén**
Petromy-zontiformes	*Geotria australis*	1651.2	Vulnerable	No		Itata, **Biobío, Imperial, Toltén, Valdivia, Bueno**
Siluriformes	*Diplomystes incognitus*	1084.5	Non classified		Yes	**Rapel, Mataquito, Maule, Itata**
Siluriformes	*Diplomystes nahuelbutaensis*	957.7	Endangered	Yes	Yes	**Biobío, Imperial**
Perciformes	*Percilia irwini*	1219.1	Endangered	Yes	Yes	**Biobío**
Osmeriformes	*Galaxias maculatus*	2250.2	Maule to north: Vulnerable; Biobío south: Less concern	No		Maipo, **Itata, Biobío, Imperial, Toltén, Valdivia, Bueno**
Perciformes	*Percilia gillissi*	3164.6	Endangered	Yes	No	**Maipo, Rapel, Mataquito, Maule, Itata, Imperial, Toltén, Valdivia, Bueno**
Perciformes	*Percichthys trucha*	2909.3	Near threaten	No		Maipo, **Rapel, Mataquito, Maule, Itata, Biobío, Imperial,** Toltén, **Valdivia, Bueno**
Atheriniformes	*Basilichthys microlepidotus*	3520	Vulnerable	Yes	No	**Maipo, Rapel, Mataquito, Maule, Itata, Biobío, Imperial, Toltén,**

						Valdivia, Bueno
Siluriformes	*Trichomycterus areolatus*	4701.4	Vulnerable	No		**Maipo, Rapel, Mataquito, Maule, Itata, Biobío, Imperial, Toltén, Valdivia, Bueno**

3.2 Hydropower projects and the need for mitigation technology

The exploitable hydropower in the study area was 12,338 GW distributed across 1124 sites. From those sites, 165 (15%) projects were located above 1500 m.s.l. and/or have optimum passability (i.e., lateral intake without barrier). Therefore, for 959 (85%) of projects, fish species would be impacted. From these sites, 219 have fish data and 740 do not.

3.2.1 Projects sites where mitigation is not required

A total of 165 planned projects do not require mitigation. Of these sites, 43 were located above 1500 m.s.l., and 122 showed an intake with optimum passability. Their exploitable hydropower was 1,532 GW.

Projects where mitigation is not required were mainly located on the Andes mountain range (81%), concentrated in the Maule and Biobío river basin (45%), and in reaches with 2-4 Strahler's order (76%). The predominant characteristics of these projects were a capacity of 3-20 MW (48%), dam height of less than 20 m (87%), Francis turbine (72%) and lateral intake without a barrier (77%) (Figure 3).

3.2.2 Project sites where mitigation is required and considered feasible

The 31 species present in the study area formed a total of 83 assemblages which comprised up to 13 species (Supl. Material S1). The most frequent genera in the different assemblages were: *Trichomycterus*, *Diplomystes*, and *Percilia*, referred to as the TDP group. A total of 87 projects were planned at sites where only species belonging to the TDP group were present. All species belonging to this group were characterized as predominantly benthic, less than 25 cm total length when adult, and exhibing subcarangiform and carangiform swimming modes (Link and Habit, 2015). Compared to the TDP group, *Cheirodon pisciculus* and *Bullockia maldonadoi* were considered to have similar fishway passage performance. Consequently, the TDP group, *Ch. pisciculus* and *B. maldonadoi* were defined as the core group of species on which development of a technical solution that could best mitigate fragmentation at the highest number of planned projects should be based. From the 219 project sites that affect fish and for which fish data is available, 90 projects (41%) maintain the core group, with an exploitable hydropower potential of 1,824 GW.

Project sites where mitigation is required and considered feasible were mainly located in the Andes mountain range (85%) of the Maule, Itata and Biobío river basin (71%), and reaches of 2-4 Strahler's order (83%). The predominant characteristics of these projects were capacity of 3-20 MW (49%), dam height of less than 20 m (74%), Francis turbines (87%), and lateral intake with a barrier (88%) (Figure 3).

3.2.3 Project sites where mitigation is required and considered challenging

A total of 129 projects are planned in river reaches represented by species other than the core group, with a variety of different assemblages that makes the development of a standard solution difficult (Supl. Material S1). This is because case-specific solutions would be required, particularly at sites with high local species richness (Figure 2a). Furthermore, there was a positive and marginaly significant correlation between the number of planned hydropower projects and fish species richness in a river basin ($y = 12.68x - 53.69$, $R^2 = 0.356$, $p = 0.071$; Figure 2b). The Biobío river basin stands out with a high number of proposed projects overlapping with high species richness.

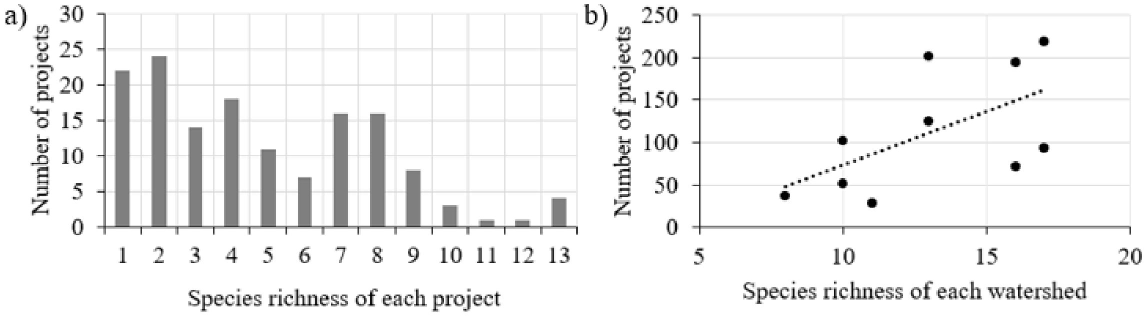


Fig. 2. Relationship between number of projects and species richness of each project (a), mean species richness of each river basin (b).

Projects sites where mitigation is required and considered challenging were mainly located in the Andes mountain range (66%), concentrated in the Biobío and Valdivia river basin (58%), in reaches with 2-4 Strahler's order (64%). The predominant characteristics of these projects were capacity of less than 30 MW (39%), dam height of less than 20 m (75%), Francis turbine (76%) and lateral intake with a barrier (85%) (Figure 3).

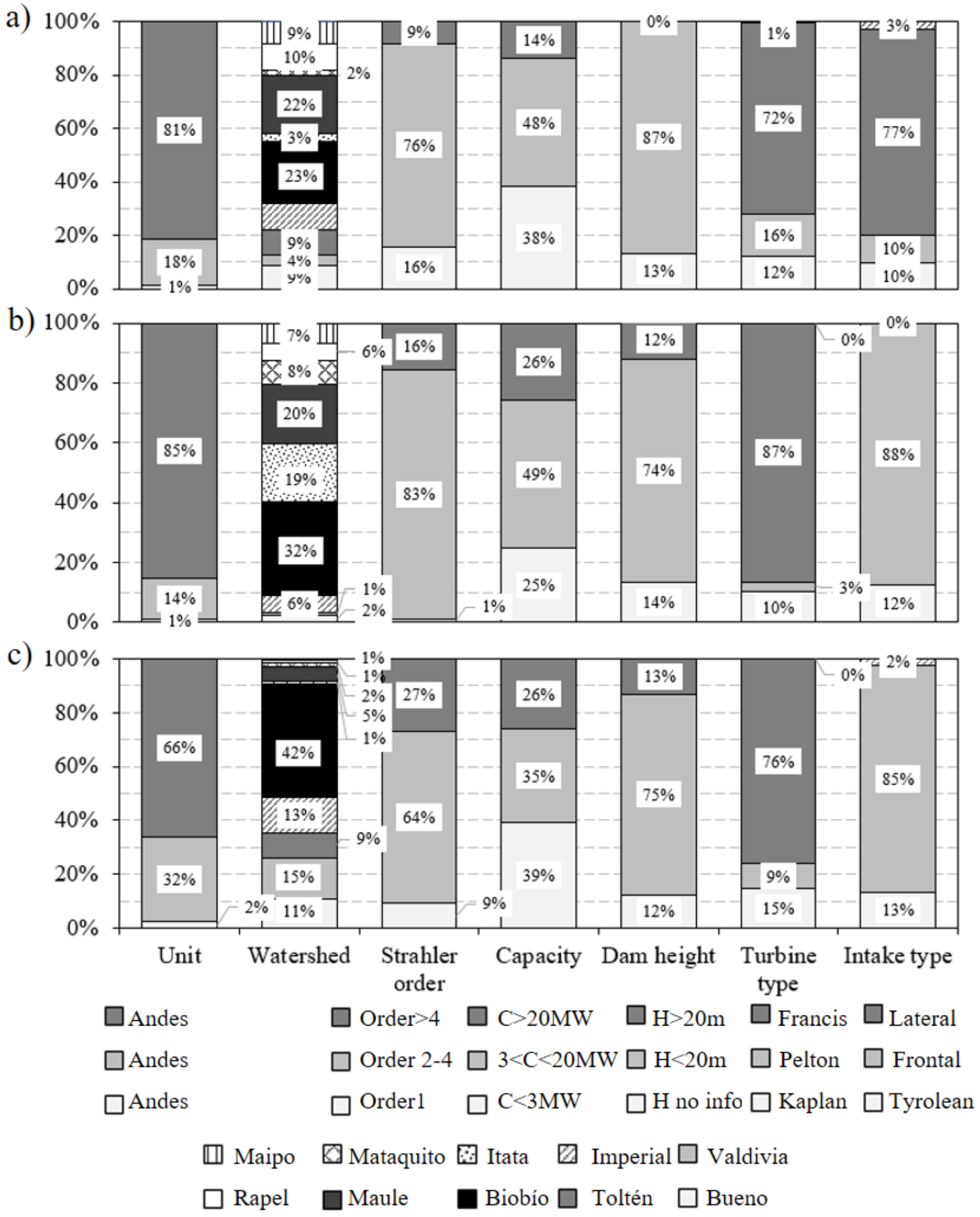


Fig. 3. Characterization (geographical unit, watershed, Strahler's order, capacity, dam height, turbine type, and water intake type) for projects where mitigation is (a) not required (165, upper panel), (b) required and considered feasible (90, center panel), and (c) required and considered challenging (129, bottom panel).

3.2.4 Generalization of results to projects with impassable barriers without fish data

Characteristics of the 219 sites with impassable barriers and fish data were compared to those of the 740 sites with impassable barriers and without fish data. The characteristics of these two project groups were similar (ANOSIM, R = 0.116, p = 0.001; Table 2). Thus, we assume that our results were representative of all the planned hydropower projects in Central Chile.

Table 2

Hydropower project characteristics where fish are expected to be impacted, with and without fish data.

Character	**Projects with fish data (219) (%)**	**Projects without fish data (740) (%)**
Coastal plain	1.8	2.4
Central valley	24.2	11.9
Andean range	74.0	85.7
Strahler’s order 1	5.9	22.8
Strahler's order 2 to 4	71.7	75.1
Strahler’s order >4	22.4	2.0
Capacity < 3MW	33.3	60.9
3 < Capacity < 20 MW	40.6	31.4
Capacity > 20 MW	26.0	7.7
Dam height < 20 m	74.4	92.2
Dam height > 20 m	12.8	2.2
Dam height unknown or no info	12.8	5.7
Kaplan turbine	12.8	16.2
Pelton turbine	6.8	22.3
Francis turbine	80.4	61.2

Turbine no info	0	0.3
Frontal intake	85.8	54.9
Tyrolean intake	12.8	35.8
Intake unknown	1.4	9.3

3.2.5 Statistical differences between site groups with different mitigation needs

Subgroups of project sites where mitigation is not required, where it is feasible and where it is challenging were similar with some differences (ANOSIM, $R_{global} = 0.165$; $p < 0.001$).

Projects sites where mitigation is required and considered feasible or challenging were different (ANOSIM, $R_{pairwise} = 0.045$; $p = 0.005$) and their differences were mainly explained by geographical unit (andes: 85%, 66%; valley: 14%, 32%; coast: 1%, 2%, feasible and hardly solution, respectively), and capacity (< 3 MW: 25%, 39%; 3-20 MW: 49%, 35%; > 20 MW: 26%, 26%, feasible and hardly solution, respectively).

Project sites where mitigation is not required and where mitigation is required and considered challenging were similar with some differences (ANOSIM, $R_{pairwise} = 0.226$; $p = 0.001$). Differences between these groups were predominantly explained by intake type (tyrolean intake: 10%, 13%; lateral intake with barrier: 10%, 85%; lateral intake without a barrier: 77%, 0%; no information: 3%, 2%, for with no need of mitigation technology and with hardly solution, respectively), and geographical unit (Andes: 81%, 66%; Central Valley: 18%, 32%; Coast: 1%, 2%, with no need of mitigation technology and with hardly solution, respectively).

Finally, project sites where mitigation is not required and where mitigation is required and considered feasible were similar with some differences (ANOSIM, $R_{paiwise} = 0.168$; $p = 0.001$). Differences between these groups were mainly explained by intake type (tyrolean intake: 12%, 10%; lateral intake with barrier: 88%, 10%; lateral intake without a barrier: 0%, 77%; no information: 0%, 3%, for with no need of mitigation technology and with feasible solution, respectively), and basin (mainly in Itata: 3%, 19%; Biobío: 23%, 32%; Toltén river basin: 9%, 0%, for with no need of mitigation technology and with feasible solution, respectively) (Figure 3).

4 Discussion

To conserve biodiversity within the constraints of limited resources, and to make management decisions in appropriate time-scales relative to the urgency of the threats and current rates of degradation of river environments, prioritization of hydropower development should be made. In this study we aimed to develop a methodology to set conservation priorities for sustainable hydropower development by analyzing the characteristics of native species and planned hydropower projects, that could be implemented in several different geographical zones, with different species distribution Hydropower projects where mitigation is not required were considered to produce only indirect impacts on native fish, mostly due to the possible alteration of the sedimentological regime and nutrients spiralling (Kemp, 2015). Other sources of impact such as injuries and mortality (e.g., blade strike, rapid pressure fluctuation, cavitation, shear stress and turbulence, Cada, 2001; Vowles *et al.*, 2014) would need to be analysed on a case-by-case basis. Projects sites where mitigation is required and considered feasible allow the development of a standard solution, such as multi-species fish passage, for the core group, as a starting point. A functional criteria based on habitat use was selected to identify the core group, as assemblages composed by the most frequent genera occurring at planned project sites. Assuming that consent for the hydropower projects would be granted, the proposed strategy suggest that projects sites where mitigation is not required should be prioritized. These projects total an installed capacity estimated to be 1,532 GW. Projects sites where mitigation is required and considered feasible should be contemplated if a mitigation technology is developed considering bounded requirements. These projects total an installed capacity estimated to be 3,904 GW. Consequently, these two subgroups of project sites (totalizing 15+35 = 50% of the planned projects, i.e. 5,437

GW) should be a prioritised considering they minimize the environmental impacts. The other projects considered challenging (50%) have the lowest priority, considering the need to develop a suitable site-specific mitigation solution.

As a result of the incentives of the Chilean Energy Policy that promotes that at least 70% of electricity generation should be from renewable sources by 2050 during the last decade the small hydropower sector increased in the Chilean energy matrix (Ministry of Energy, 2015; Arriagada *et al.*, 2019) and many hydropower projects are planned for the near future. Until now, no hydropower projects have been built with a fishway provided.

There was no difference in the physical characteristics of sites where fish were expected, but this should be viewed with caution considering the absence of data in many cases. It could be assumed that the results obtained for sites with fish data are representative of the sites without. Consequently, in 35% of the projects where fish species were predicted to be impacted, habitat fragmentation could found a solution with a feasible mitigation technology (equivalent to 394 sites), and in 50% of them (equivalent to 565 sites), the mitigation technology will be hardly achievable. A variety of devices have been installed at river barriers to restore connectivity as mitigation technology worldwide. The most common devices to assist displacements are fishways, structures that allow fish to swim upstream under their own effort (Clay, 1995). Mitigation technologies also include physical screens and surface bypasses, intended to prevent juveniles from passing through turbines (Larinier, 2001; Noatch and Suski, 2015). The extrapolation of the results to other projects without fish data based on the project characteristics was performed in an effort to estimate the magnitude of the challenge, and in an effort to overcome the scarcity of data which is common in neotropics. Caution must be taken when interpreting the results of such as an extrapolation, particularly when forming generalised conclusions related to the nature of impact on fish species. Consecutive studies should test this prediction. For any project, a developer should verify the basic information related to fish species present and the project characterization, before deciding if mitigation technology recommended should be incorporated into the design.

Species with the greatest distribution along the river network or concentrated in the upper part of the rivers will be the most affected by future hydropower development in Chile as the potential is mainly concentrated in the Andean mountain range and in the Central Valley. Seven species do not overlap with any planned projects (*Cheirodon kiliani, D. chilensis, Brachygalaxias gothei, Mugil cephalus, Aplochiton marinus, Odontesthes brevianalis and O. itatanum*), and eight occur at more than 45 projects sites each (*T. areolatus, B. microlepidotus, P. trucha, P. gillissi, P. irwini, G. maculatus, D. nahuelbutaensis* and *D. incognitus*). Of particular concern is the situation of *D. nahuelbutaensis, D. incognitus* and *P. irwini*, endemic to the study area, and present in at least in 49 projects sites. Moreover, although *B. microlepidotus, P. trucha* and *G. maculatus* were not part of the core group, they occurred in more than 67 projects sites. However, together these species would be impacted by only 13 projects and in other identified assemblages always co-occurred with different species. Thus, a solution for these assemblages needs to be developed on a case-by-case basis. At the watershed scale, the positive relationship between species richness and number of hydropower projects is also a cause for concern. This relation suggests that characteristics of the river networks that sustain greater biodiversity are also suitable for hydropower development.

The need to develop novel and innovative approaches for advancing Chilean native fish passage has been driven by the threat of a high pressure to develop hydropower (Habit *et al*., 2019). In Chile, efforts have been made by Laborde *et al.* (2016) and Link *et al.* (2017) to provide hydraulic design criteria for native species, while elsewhere others are also attempting to develop fish passage design criteria that cater for a wider range of target species (Silva *et al.*, 2012; Muraoka *et al.*, 2017). In this study, a core group (comprising the TDP group, *Ch. pisciculus* and *B. maldonadoi*) has been identified as a starting point to advance fishway development for Chilean species exposed to hydropower projects. The core group was composed of small-bodied, benthic, nocturnal, benthofagous and resident species. In Chile, the genus *Trichomycterus* is represented by the widespread species *T. areolatus* and the endemic species *T. chiltoni*; *Percilia* by two endemic species, *P. irwini* and *P. gillissi*; and *Diplomystes* by four endemic species, *D. chilensis, D. incognitus, D. nahuelbutaensis* and *D. camposensis*. *Cheirodon pisciculus* and *B. maldonadoi* are also endemic. Within these groups, *B. maldonadoi* and all species of *Diplomystes* and *Percilia* have been classified as endangered. Solutions developed for the TDP group would likely be applicable to several other species of the same genera with similar biology (e.g. *T. aerolatus* and *T. chiltoni*, Pardo *et al.* 2005; *D. nahuelbutaensis, D. camposensis, D. incognitus,* and *D. chilensis,* Beltrán-Concha *et al.*, 2012; Arratia and Quezada-Romegialli, 2017).

5 Conclusion

The potential conflict associated with plans to exploit substantial hydropower potential and the requirement to protect unique native freshwater fish fauna emphasizes the need for mitigation technologies, such as fish passes.

Following the proposed strategic methodology to set priorities for sustainable hydropower development in a biodiversity hotspot, three categories of projects were identified according to their need for mitigation technology, namely project sites where mitigation is: (1) not required (15%), (2) required and considered feasible (35%), and (3) required but considered challenging (50%).

Further research on species characteristics belonging to the core group is needed to advance appropriate fishway technologies. Even when fishways have been recognized as half-way technologies (Kemp 2016), as their effectiveness can be low in many cases, the development of a fishpass for the identified core group of species would contribute to more sustainable hydropower development.

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Table S1.

Assemblages, river watersheds and planned projects.

Assemblage Nr.	**Species richness**	**Assemblage**	**River watersheds**	**Number of projects**
1	1	*P. trucha*	Valdivia	1
2	1	***T**. chiltoni*	Biobío	1
3	1	*Ch. pisciculus*	Rapel	1
4	1	***P**. irwini*	Biobío	1
5	1	*G. platei*	Bueno	2
6	1	*A. zebra*	Valdivia, Bueno	2
7	1	*O. mauleanum*	Bueno	3
8	1	***P**. gillissi*	Rapel, Itata	3
9	1	*B. microlepidotus*	Biobío	4
10	1	*G. australis*	Imperial	4
11	1	*G. maculatus*	Toltén, Valdivia	6
12	1	***D**. incognitus*	Mataquito, Maule	11
13	1	***T**. areolatus*	Maipo, Maule, Itata, Biobío,	23

			Imperial Bueno	
14	2	*G. australis, Ch.australe*	Valdivia	1
15	2	***P***. *gillissi*, ***D***. *camposensis*	Valdivia	1
16	2	***P***. *gillissi*, ***T***. *aerolatus*	Itata	1
17	2	*G. maculatus, A. taeniatus*	Toltén	1
18	2	***T***. *areolatus, G. australis*	Imperial	1
19	2	***T***. *areolatus, P. trucha*	Maule, Biobío	1
20	2	*B. microlepidotus, P. trucha*	Biobío	1
21	2	***T***. *areolatus, A. taeniatus*	Toltén	2
22	2	*G. maculatus, G. australis*	Valdivia	2
23	2	*B. microlepidotus*, ***P***. *gillissi*	Maule	2
24	2	***T***. *areolatus*, ***D***. *nahuelbutaensis*	Biobío	2
25	2	*P. trucha, O. mauleanum*	Bueno	3
26	2	***T***. *areolatus*, ***T***. *chiltoni*	Biobío	3
27	2	***T***. *areolatus, G. maculatus*	Valdivia, Toltén	4
28	2	***D***. *nahuelbutaensis; P. melanops*	Biobío	6
29	2	***P***. *gillissi;* ***D***. *incognitus*	Maule, Itata	6
30	2	***T***. *areolatus*, ***D***. *incognitus*	Rapel, Mataquito, Maule, Itata	11
31	2	***T***. *areolatus*, ***P***. *irwini*	Biobío	14
32	3	***T***. *aerolatus, G. maculatus*, ***P***. *irwini*	Biobío	1
33	3	***T***. *aerolatus*, ***P***. *gillissi, P. trucha*	Mataquito	1

34	3	*B. microlepidotus, O.mauleanum, P.trucha*	Valdivia	1
35	3	*B. microlepidotus,* ***P****. irwini, P.trucha*	Biobío	1
36	3	*G. australis, G. maculatus,* ***P****. gillissi*	Imperial	1
37	3	*G. maculatus, G. platei, A. teaniatus*	Valdivia	1
38	3	***T****. aerolatus, B. maldonadoi, P. trucha*	Biobío	2
39	3	*G. maculatus, G. platei, O. mauleanum*	Bueno	2
40	3	***T****. aerolatus, B. microlepidotus,* ***P****. gillissi*	Maule	2
41	3	***T****. aerolatus,* ***D****. nahuelbutaensis,* ***P****. irwini*	Biobío	2
42	3	***T****. aerolatus, B. microlepidotus, P. trucha*	Biobío	2
43	3	***T****. aerolatus,* ***P****. gillissi,* ***D****. incognitus*	Mataquito, Maule, Itata	8
44	4	*G. australis,* ***T****. aerolatus, G. maculatus,* ***P****. gillissi*	Imperial	1
45	4	*G. australis,* ***T****. aerolatus, G. maculatus,* ***P****. irwini*	Biobío	1
46	4	*B. maldonadoi,* ***T****. aerolatus, G. maculatus, A. taeniatus*	Toltén	1
47	4	***T****. aerolatus, B. microlepidotus,* ***P****. gillissi,* ***D****. incognitus*	Maule	1
48	4	*G. platei, A. zebra,* ***P****. gillissi, P.trucha*	Bueno	1
49	4	*B. maldonadoi,* ***T****. aerolatus,* ***D****. nahuelbutaensis,* ***P****. irwini*	Biobío	2
50	4	***T****.aerolatus, G. maculatus, B. microlepidotus, O, mauleanum*	Valdivia	4
51	4	***T****. aerolatus,* ***D****.nahuelbutaensis,* ***P****. irwini,*	Biobío	4

		P. trucha		
52	4	*N. inermis, **T**. aerolatus, **D**. nahuelbutaensis, **P**. irwini*	Biobío	5
53	5	*B. maldonadoi, **T**. chiltoni, **T**. aerolatus, **D**. nahuelbutaensis, P. trucha*	Biobío	1
54	5	*Ch. pisciculus, **T**. aerolatus, B. microlepidotus, **P**. gillissi, P. trucha*	Mataquito	1
55	5	*Ch. pisciculus, **T**. aerolatus, B. microlepidotus, **P**. gillissi, P. melanops*	Maipo	1
56	5	***T**. aerolatus, G. maculatus, B. microlepidotus, **P**. gillissi, P. trucha*	Bueno	1
57	5	*B. maldonadoi, **T**. aerolatus, **D**. nahuelbutaensis, **P**. irwini, P. trucha*	Biobío	1
58	5	*G. australis, N. inermis, **D**. nahuelbutaensis, G. maculatus, **P**. irwini*	Imperial	3
59	5	*M. lapicida, **T**. aerolatus, G. maculatus, A. zebra, **P**. irwini*	Biobío	3
60	6	*G. australis, N. inermis, **T**. aerolatus, **D**. nahuelbutaensis, G. maculatus, **P**. irwini*	Biobío	1
61	6	*N. inermis, **T**. aerolatus, G. maculatus, B. microlepidotus, **P**. irwini, P. trucha*	Biobío	1
62	6	*Ch. pisciculus, N. inermis, **T**. aerolatus, B. microlepidotus, **P**. gillissi, P. trucha*	Rapel	1
63	6	*G. australis, N. inermis, **T**. aerolatus, **D**. nahuelbutaensis, G. maculatus, **P**. irwini*	Biobío	1

64	6	*G. australis*, ***T**. aerolatus*, ***D**. nahuelbutaensis*, *G. maculatus*, ***P**. gillissi*, *P. trucha*	Imperial	1
65	6	*B. maldonadoi*, ***T**. aerolatus*, ***D**. nahuelbutaensis*, *B. microlepidotus*, *P. trucha*, *P. melanops*	Biobío	1
66	6	***T**. aerolatus*, ***D**. nahuelbutaensis*, *G. maculatus*, *B. microlepidotus*, ***P**. irwini*, *P. trucha*	Biobío	1
67	7	*G. australis*, *M. lapicida*, *Ch. australe*, ***T**. aerolatus*, *G. maculatus*, *B. microlepidotus*, ***P**. gillissi*	Toltén	1
68	7	*Ch. galusdae*, *N. inermis*, ***T**. aerolatus*, *B. microlepidotus*, ***P**. gillissi*, *P. trucha*, ***D**. incognitus*	Maule	1
69	7	*G. australis*, *Ch. galusdae*, *B. maldonadoi*, *G. maculatus*, *B. microlepidotus*, ***P**. gillissi*, *P. trucha*	Imperial	3
70	7	*Ch. galusdae*; *B. maldonadoi*; ***T**. areolatus*; ***D**. nahuelbutaensis*; *B. microlepidotus*; ***P**. irwini*; *P. trucha*	Biobío	8
71	8	*G. australis*, ***T**. aerolatus*, ***D**. nahuelbutaensis*, *G. maculatus*, *B. bullocki*, *B. microlepidotus*, ***P**. gillissi*, *P. trucha*	Imperial	1
72	8	*M. lapicida*, ***T**. aerolatus*, *G. maculatus*, *G.*	Valdivia	1

		*platei, A. taeniatus, B. microlepidotus, **P**. gillissi, P. trucha*		
73	8	*G. australis, M. lapicida, **T**. aerolatus, G. maculatus, B. microlepidotus, O. mauleanum, **P**. gillissi, P. melanops*	Toltén	1
74	9	*G. australis, Ch. australis, **T**. aerolatus, G. maculatus, G. platei, B. bullocki, B. microlepidotus, **P**. gillissi, P. trucha*	Bueno	1
75	9	*Ch. galusdae, B. maldonadoi, **T**. aerolatus, G. maculatus, B. bullocki, B. microlepidotus, **P**. gillissi, P. trucha, **D**. incognitus*	Itata	1
76	9	*G. australis, Ch. galusdae, B. maldonadoi, **T**. aerolatus, **D**. nahuelbutaensis, G. maculatus, B. microlepidotus, **P**. gillissi, P. trucha*	Imperial	2
77	9	*Ch. galusdae, B. maldonadoi, **T**. aerolatus, **D**.nahuelbutaensis, G. maculatus, B. microlepidotus, O. mauleanum, **P**. irwini, P. trucha*	Biobío	4
78	10	*Ch. galusdae, N. inermis, B. maldonadoi, **T**. chiltoni, **T**. aerolatus, **D**.nahuelbutaensis, B. microlepidotus, O. mauleanum, **P**. irwini, P. trucha*	Biobío	1
79	10	*Ch. galusdae, B. maldonadoi, **T**. chiltoni,*	Biobío	2

		__T__. aerolatus, __D__.nahuelbutaensis, B. microlepidotus, O. mauleanum, __P__. irwini, P. trucha, P. melanops		
80	11	*G. austral, M. lapicida, Ch. australe, __T__. aerolatus, __D__. camposensis, G. maculatus, G. platei, B. microlepidotus, O. mauleanum, __P__. gillissi, P. trucha*	Valdivia	1
81	12	*G. australis, M. lapicida, Ch. galusdae, B. maldonadoi, __T__. aerolatus, __D__.nahuelbutaensis, G. maculatus, B. microlepidotus, O. mauleanum, __P__. irwini, P. trucha, P. melanops*	Biobío	1
82	13	*G. australis, Ch. australe, __T__. aerolatus, H. macraei, __D__. camposensis, G. maculatus, G. platei, B. bullocki, A. taeniatus, B. microlepidotus, O. mauleanum, __P__. gillissi, P. trucha*	Valdivia	2
83	13	*G. australis, Ch. australe, __T__. aerolatus, H. macraei, __D__. camposensis, G. maculatus, G. platei, A. zebra, A. taeniatus, B. microlepidotus, O. mauleanum, __P__. gillissi, P. trucha*	Valdivia	2

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships
that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Fish species that are most at risk for hydropower development were identified.
- Planned projects were categorized based on their need for mitigation of impacts.
- The finding emphasizes the need to develop a multispecific fishway.