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Fragmentation of Chilean Andean rivers: expected effects of hydropower development

Gustavo Díaz[1*], Pedro Arriagada[2], Konrad Górski[3,4], Oscar Link[5], Bruno Karelovic[6], Jorge Gonzalez[1] and Evelyn Habit[1,7]

Abstract

Background: Fragmentation (establishment of barriers e.g., hydropower dams, reservoirs for irrigation) is considered one of the greatest threats to conservation of river systems worldwide. In this paper we determine the fragmentation status of central Chilean river networks using two indices, namely Fragmentation Index (FI) and Longest Fragment (LF). These are based on the number of barriers and their placement as well as river length available for fish movement. FI and LF were applied to eight Andean river basins of central Chile in order to assess their natural, current (2018) and future (2050) fragmentation at the doorstep of a hydropower boom. Subsequently, we exemplify the use of these indices to evaluate different placement scenarios of new hydropower dams in order to maximize hydropower use and at the same time minimize impact on fish communities.

Results: In the natural scenario 4 barriers (waterfalls) were present. To these 4 barriers, 80 new ones of anthropogenic origin were added in the current (2018) scenario, whereas 377 new barriers are expected in near future (2050). Therefore, compared to the 'natural' scenario, in 2050 we expect 115-fold increase in fragmentation in analysed river systems, which is clearly reflected by the increase of the FI values in time. At the same time, the LF diminished by 12% on average in the future scenario. The fastest increase of fragmentation will occur in small and medium rivers that correspond to 1st, 2nd and 3rd Strahler orders. Finally, case study on configuration of potential hydropower plants in the Biobío basin showed that hydropower output would be maximized and negative effects on fish communities minimised if new hydropower plants would be located in tributaries of the upper basin.

Conclusions: Fragmentation of Chilean Andean river systems is expected to severely increase in near future, affecting their connectivity and ecological function as well as resilience to other anthropogenic stressors. Indices proposed here allowed quantification of this fragmentation and evaluation of different planning scenarios. Our results suggest that in order to minimise their environmental impact, new barriers should be placed in tributaries in the upper basin and river reaches above existing barriers.

Keywords: Connectivity, Dams, Hydroelectricity, Fragmentation index, Native fish

Background

River systems are hierarchical dendritic networks and their functioning strongly depends on physical connectivity [1–3]. Fragmentation (establishment of any type of barriers e.g., dams, reservoirs for irrigation) and consequent loss of connectivity are considered one of the greatest threats to conservation of river systems worldwide [4]. It impedes fundamental eco-hydrological processes in river systems affecting the hydrologic, sediment, and temperature regimes; channel morphology, nutrient cycling, interactions with floodplains and consequently impacts riverine biota [5–8]. For example, fragmentation has been documented to affect the structure of biotic communities, alter migrations, and limit dispersion of riverine organisms [9–11]. Therefore, fragmentation is expected to be detrimental to the ecological functioning of river systems and conservation of biota that

* Correspondence: gusdiaz@udec.cl
[1]Departamento de Sistemas Acuáticos, Facultad de Ciencias Ambientales, Universidad de Concepción, P. O. Box. 160-C, Concepción, Chile
Full list of author information is available at the end of the article

inhabits them [7, 12, 13]. Still, in recent decades there has been an explosive increase in the number of barriers in river systems worldwide, mostly in relation to hydropower development [14]. At the same time, new conceptual frameworks to advance understanding of physical, hydrologic, and ecological aspects of connectivity have been proposed and new metrics and indices to quantify fragmentation have been developed [15–18]. Indices to quantify fragmentation need to be based on theoretical principles of connectivity and hierarchical nature of river networks [19]. Often, fragmentation of the river network is represented through indices of longitudinal connectivity of the physical habitat of fish species, because fishes are the most vagile aquatic organisms, and their movements are crucial to complete their life cycle and maintenance of populations [9, 20]. In this way, Cote et al. [15] proposed Dendritic Connectivity Index (DCI) to assess habitat connectivity for fish with different life-histories (potadromous; DCI_P and diadromous; DCI_D) on a scale of a river network (basin). This index incorporated three variables: number of barriers, placement (location within the network) and passability (probability to cross a barrier). Thus, for resident or potamodromous fish, connectivity is expected to depend more on the "largest fragment", whereas for diadromous fish it depends on the position of the barrier in relation to the river mouth [15]. This index has been successfully used to assess effects of fragmentation on diversity, abundance and distribution patterns of riverine fish in some river systems [21–23]. Some limitations of DCI have also been recognised, most importantly the consideration of the barrier placement only as a theoretical approximation expressed as the distance to the lowest point of the network [17] included an additional metric for placement of barriers within the river network, namely the river volume related to discharge and channel dimensions. This approach, however, strongly relies on data availability and may not be suitable for river basins where detailed hydrologic data are not available.

Worldwide, rapid population growth and energy demand combined with increased consciousness about climate change and need of reduction of the emissions of greenhouse gases have led to hydropower boom with various projects of hydropower plants under construction or planned [14]. These projects are unequally distributed across the globe with most of them concentrated in South America, South-East Asia and the Balkans in Europe [14, 24]. In South America hydropower plant projects concentrate in Andean regions of various countries including Chile [25]. Currently, in the Chilean energy matrix hydroelectricity accounts for 35% and this percentage is expected to grow due to policies promoting the reduction of greenhouse gases and the exploitable hydropower potential estimated at 11 GW spread in approximately 1500 sites [26]. These new projected barriers are expected to increase the current fragmentation status of Chilean river systems. Thus, there is a strong need to quantify fragmentation and evaluate different planning scenarios of hydropower plant placement [27]. To support decision making processes towards the conservation of the unique Andean river systems that are inhabited by fauna of extremely high level of endemism (e.g., 82% of fish species in Chilean freshwater systems are endemic to Chile; [28]). In addition, for majority of the river systems in Chile, detailed hydrological data are not available, and therefore, calculation of hydrological variables needed in order to use recently proposed indices that consider placement of barriers is difficult [17].

This study aims to compare the physical fragmentation level of Andean Chilean rivers among three different scenarios: 'natural' (before anthropogenic intervention), current (2018), and scenario expected in near future (2050) based on present hydropower development plans. To do this, we quantify fragmentation status of eight Andean rivers of central Chile in each of the scenarios using two newly developed indices that consider placement of barriers and are suitable for river basins with poor hydrological data availability: Fragmentation index (FI) and Longest fragment index (LF). We use Strahler order as an easy to obtain metric that represents placement of the barrier within the basin. Subsequently, on the example of one of the analysed basins with the highest hydropower potential (the Biobío basin), we evaluate a range of configurations of hydropower plants using our indices and compare them to distribution of native fish within the basin. Finally, we discuss implications of temporal changes in level of fragmentation of these systems for their ecological function.

Methods

Study area

The study area is located in central Chile, and comprises eight river basins (river networks) namely: Aconcagua, Maipo, Rapel, Mataquito, Itata, Biobío, and Imperial (32°S - 38°S; Table 1 and Fig. 1). From Aconcagua to Biobío the rivers are characterised by discharge regimes dominated by rainfall and snowmelt, and rapid flows, because of their steep slopes. Imperial River originates at a lower altitude in the piedmont of the Andes and thus, it lacks torrential flows [29, 30]. In addition, these river basins show differences in their catchment area, total length of river network and maximal Strahler order, where Biobío river basin is the largest among all assessed basins (Table 1). All basins of the study area belong to the same ichthyogeographic province [31]. This province is the most diverse in Chile and accommodates a total of 21 native and 15 non-native fish species [28]. Native freshwater fish present a high endemism and primitivism level, and are of high conservation interest [32]. Most of native species are characterised by small body sizes

Table 1 Geographical and physical features of eight studied river networks. Latitude indicates the northern and southern boundaries, whereas Longitude indicates eastern and western boundaries of each river network

Basin	Latitude (°)	Longitude (°)	Area (km^2)	Length (km)	Maximum Strahler order
Aconcagua	32°15′-33°11′ S	69°59′-71°33′ W	7334	3671	5
Maipo	32°56′-34°18′ S	69°48′-71°38′ W	15,274	8216	7
Rapel	33°54′-35°00′ S	70°01′-71°51′ W	13,766	5915	6
Mataquito	34°48′-35°38′ S	70°24′-72°11′ W	6332	2879	5
Maule	35°06′-36°35′ S	70°21′-72°27′ W	21,053	8532	6
Itata	36°12′-37°20′ S	71°02′-72°52′ W	11,327	4887	6
Biobío	36°52′-38°54′ S	70°50′-73°12′ W	24,370	10,789	7
Imperial	37°49′-38°58′ S	71°27′-73°30′ W	12,668	6370	6

and therefore are expected to have limited swimming capacities [30].

Assessment of fish distribution in the Biobío basin

Current distribution of native fish in the Biobío basin was assessed by field sampling in low-flow conditions in January of 2017 (austral summer). We sampled a total of 25 sites across the basin, using backpack electrofishing equipment (Halltech HT-2000, Ontario, Canada). At each site, riffle and pool habitats were sampled to capture the majority of fish species. Specimens collected from different local communities were identified to species level according to available identification keys and returned to their original habitats [31, 33, 34]. A total of 9 native fish species were captured in both habitat types, and the most representated order was Siluriformes with three species (Table 2). Furthermore, *Percilia irwini* Eigenmann, 1928 and *Trichomycterus areolatus* (Valenciennes, 1840) occurred most frequently across sampling sites (> 90% of sampling sites).

River networks and barriers

We used the official river hydrographic network data from the Chilean Ministry of Social Development (MIDEPLAN; Ministerio de Desarrollo Social) to assess river networks of analysed basins. This dataset is based on cartographic data from the Military Geographic Institute of Chile (IGM, 1:250.000) and is verified since 2005 by national agencies via field observations to contain only perennial rivers.

To determine the fragmentation status in the study area we overlayed these river networks with shapefile containing georeferenced barriers. Data in this shapefile were obtained from different available data bases from governmental entities related to energy policies, energy production and the use of natural resources (see below). Based on these the final dataset was compiled that contained location and type of barriers. These data were used to create three scenarios:

1) Natural scenario: impassable waterfalls higher than 20 m, since these have certainly involved a historical interruption of free movement upstream. They were identified in Google Earth photographic database and verified in the field (during 2017).
2) Current (2018) scenario: physical barriers that completely obstructed the cross-section of the river, i.e. the barrier width was equal to the width of the active channel, as well as hydroelectric barriers with generation capacity higher than 3 MW. These data were obtained for operating hydropower plants, tailings dams, and water diverting structures and reservoirs for irrigation registered in the databases of the Chilean Ministry of National Assets (Ministerio de Bienes Nacionales [35]); http://www.geoportal.cl/visorgeoportal/) and the Chilean Ministry of Energy (Ministerio de Energía [36]); http://sig.minenergia.cl/sig-minen/moduloCartografico/composer/).
3) Future (2050) scenario: barriers in this scenario included those of the current (2018) scenario, and potential barriers based on analyses of hydropower potential of the rivers performed by the Chilean Ministry of Energy. Sites with hydropower potential higher than 3 MW were included to allow comparisons with the current (2018) scenario. These data were obtained from the database of the Chilean Ministry of public works (Ministerio de Obras Públicas [37]); http://walker.dgf.uchile.cl/Explorador/DAANC/). We are aware that this future scenario is an approximation as it depends on whether hydropower development plans will not change in the future and it excludes probable barriers unrelated to hydroelectricity.

Assessment of fragmentation level

Fragmentation level was evaluated for these three scenarios using two indices: Fragmentation index (*FI*) and Longest fragment (*LF*) that were formulated based on principles proposed by *DCI* [15].

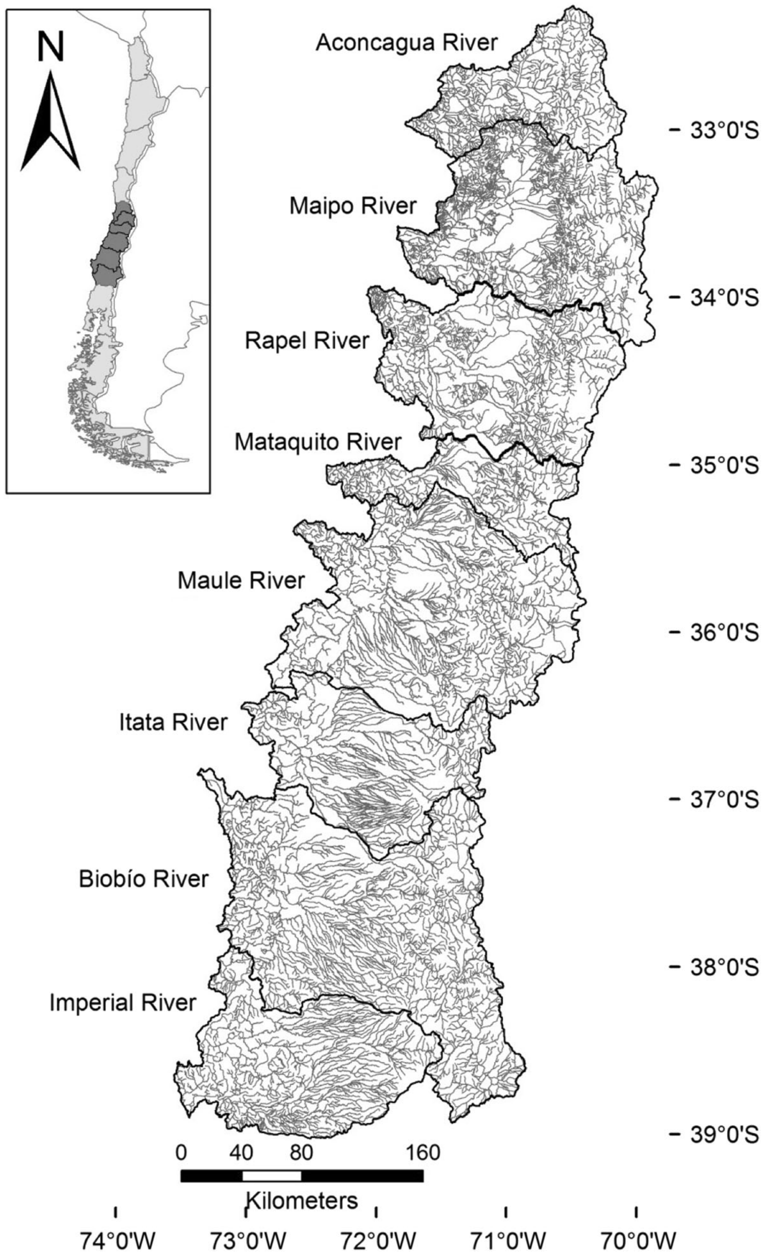

Fig. 1 Location the study area which comprises eight river network of central Chile

The functioning of *FI* is explained in Fig. 2 that shows how a barrier fragments the river network generating disconnected stretches up and downstream (L_1 to L_5 in Fig. 2). A fragment is composed of 1) river stretches upstream of a barrier, 2) the river network located between two barriers, or, 3) the river network located downstream of the barrier closest to the mouth of the river. Fragments upstream of several barriers are considered more impacted/disconnected. The way a barier affects river network strongly depends on its location [7, 38, 39] and, therefore, barrier placement in the network needs to be considered in the fragmentation index . Herein it was considered through the Strahler order of river stretch where the barrier is located (Fig. 2). Thus we calculate the impact of each barrier *i* on the fragmentation index following (Eq. 1):

$$IFI(i) = \frac{\sum_{j=1}^{M} L_j S_j}{T} \quad (1)$$

Table 2 Native fish species found in the Biobio river basin and some of their ecological features conservation status. Native fish species considered in planning optimisation case study are symbolised with asterisk (*)

Species	Habitat use	Conservation category	Endemic
Cheirodon galusdae Eigenmann, 1928	Pelagic	Vulnerable	Yes
Bullockia maldonadoi (Eigenmann, 1928)*	Benthic	Endangered	Yes
Trichomycterus areolatus (Valenciennes, 1840)	Benthic	Vulnerable	No
Diplomystes nahuelbutaensis Arratia, 1987*	Benthic	Endangered	Yes
Galaxias maculatus (Jenyns, 1842)*	Pelagic	Less concern	No
Basilichthys microlepidotus (Jenyns, 1841)*	Pelagic	Vulnerable	Yes
Ondontesthes mauleanum (Steindachner, 1836)	Pelagic	Vulnerable	Yes
Percichthys trucha (Valenciennes, 1833)*	Pelagic	Less concern	No
Percilia irwini Eigenmann, 1928	Pelagic	Endangered	Yes

Where M is the number of stretches in the river network upstream of the barrier, whereas L_j and S_j are the length and the Strahler order, respectively, of each stretch in the river network upstream of the barrier. In order to normalise this value, it is divided by T that is the maximum value that numerator of *IFI(i)* could reach, therefore, $T=\sum_{j=1}^{N} L_j S_j$, where L_j and S_j are defied as above and N is the number of stretches in all the river network. In other words, if the river network has a single barrier i located in the mouth of the river, *IFI(i) = 1*.

As such that the sum of *IFI(i)* over all the barriers in the river, i.e., $\sum_{i=1}^{N} IFI(i)$ where N is the number of barriers, could reach values higher than 1 (Fig. 2). Hence, we apply a function over $\sum_{i=1}^{N} IFI(i)$ that maps this sum into values between 0 and 1. A direct candidate is an exponential function (Eq. 2):

$$FI = 1-1.5^{-\sum_{i=1}^{N} IFI(i)} \quad (2)$$

Therefore, *FI* takes values between 0 and 1. The level of fragmentation increase with the number and length of fragments that are disconnected within the river network, and with the Strahler order of the fragment (Fig. 3). Thus, values close to 0 indicate little or no fragmentation, while values close to 1 indicate strong fragmentation of the network. The impact of barriers in reaches with high Strahler order (i.e., lower reaches of the network) was considered to be greater because the specific richness of native fish fauna increases in lower reaches of the network and therefore the potential number of species affected increases, and because the accessibility of most of the river network for diadromous species is affected more strongly by these barriers.

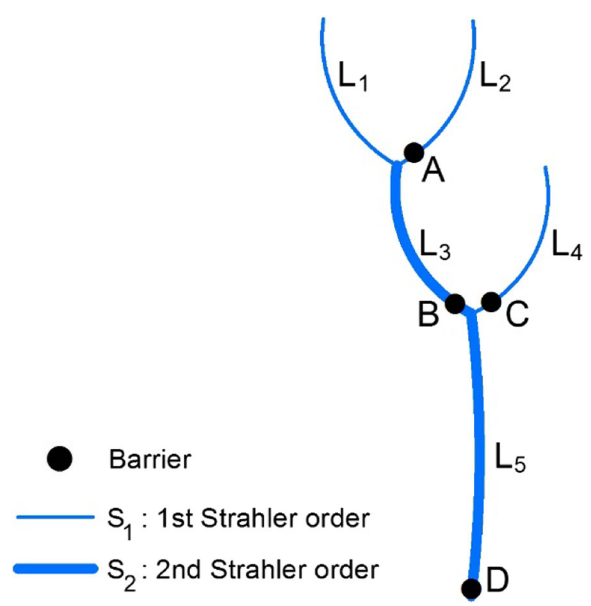

Fig. 2 River network with five stretches such that $L_1 = L_2 = L_3 = L_4 = 1$, $L_5 = 2$, and $S_1 = S_2 = S_4 = 1$, $S_3 = S_5 = 2$. Then $T=\sum_{j=1}^{5} L_j S_j = 9$. For barriers **a**, **b**, **c** and **d** we can calculate IFI (**a**) = 1/9, IFI (**b**) = 4/9, IFI (**c**) = 1/9 and IFI (**d**) = 1 respectively. Hence, $\sum_{i\in\{A,B,C,D\}} IFI(i) = 15/9$. Then FI (**a**) = 0.044, FI (**b**) = 0.164, FI (**c**) = 0.044, and FI (**d**) = 0.333 (See text for more details)

Cote et al. [15] recognised passability as an important variable to estimate habitat connectivity. Passability, however, is difficult to approximate due to specificity of design of each barrier as well as physiology, morphometric of fish and environmental conditions [40].

Quantification of passability remains a challenge and necessitates specific barrier design and fish characteristics data. Furthermore, probability to pass different barriers is not necessarily independent. We are not able to make quantification, but based on small body size and low swimming capacity of most of the fish species in our study area we assumed passability of all these barriers is very low or null [41].

To estimate the available river section for fish movement, we calculate the Longest fragment of the basin (*LF*). *LF* quantifies the maximum length available for fish to move within the river network. This length can be found between two barriers or one barrier and a river

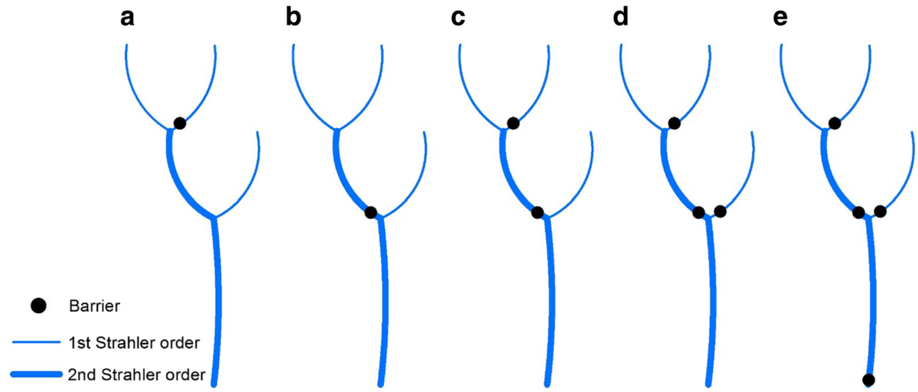

Fig. 3 Examples of different levels of fragmentation for river network shown in Fig. 1. For case **a** we have $\sum_i IFI(i) = 1/9 = 0.111$, then $FI = 1 - 1.5^{-0.111} = 0.04$; Likewise for cases **b**, **c**, **d** and **e** and we have respectively $FI = 0.16$, $FI = 0.20$, $FI = 0.24$, $FI = 0.49$

network boundary (headwaters or river mouth) and, thus was calculated as the ratio of the length of the longest fragment to the total length of the network in each basin. *LF* was calculated based on (Eq. 3):

$$LF = \frac{L_M}{L_T} \tag{3}$$

where, L_M is the length of the longest fragment in the river network and L_T is the total length of this network.

LF represents a basic but different index to assess the river fragmentation level than *FI*. Its values are close to 0 when the available network to fish movement is very small in comparison to total network length and close to 1 when available network is similar to total length of the network. *FI* and *LF* have a negative relationship, and *FI* increase when a barrier is added to the network in any fragment, whereas *LF* decreases only when a barrier is added in the longest fragment.

Planning optimisation: case study of the Biobío basin

To inform planning of potential hydropower plants in the Biobío basin, we evaluate a range of configurations of hydropower plants using our indices and compare them to distribution of native fish within the basin. These planning scenarios were built by adding potential future dams to current scenario, and resulted in four potential scenarios (in the parentheses a total expected production, including existing hydropower plants): new barriers only in the mainstem (4001 MW), new barriers only in tributaries in the lower basin (3512 MW), new barriers only in tributaries in the upper basin (3943 MW), all potential new barriers (5696 MW). Subsequently, field-assessed distribution (based on presence /absence data) of five native fish species of the highest conservation value (Table 2) was projected on these scenarios.

Results

Only three out of eight analysed river networks were characterised by natural barriers (waterfalls): Maule with two waterfalls, Itata and Biobío with one waterfall each. In the natural scenario, IF was close to 0 in all study basins (Fig. 4, Table 3). For current scenario the basin with the highest number of barriers is Maule (24 barriers) followed by Biobío (19 barriers). Itata and Imperial basins are characterised by one barrier each in the current scenario. Rapel and Biobio basins showed the highest FI values (0.463 and 0.436, respectively), whereas the lowest values of the FI were found for the Imperial (0.002) and Itata (0.044) basins (Table 3). In the future (2050) scenario a total of 461 barriers is expected in all analysed basins. There is an increase in the total number of barriers in all basins (Fig. 4, Table 3). The Biobío basin showed the highest increase in number of barriers between the current (19 barriers) and future (158 barriers) scenarios and the highest FI in the future scenario (0.936). Also Maule basin is expected to accommodate 65 new barriers in the future scenario in comparison to 24 in the current scenario. Furthermore, Itata and Imperial basin are expected to accommodate, 38 and 47 new barriers, respectively (Table 3). The basin with the lowest increase of the value of FI between the current (2018) and the future (2050) scenario was the Aconcagua (~ 0.16-fold increase caused by four new barriers), whereas Imperial showed the highest increase in the FI value (~ 190-fold caused by 46 new barriers, Table 3). Despite this, Imperial showed the lowest FI value (0.381) in the future scenario.

The longest fragment (LF) in the 'natural' scenario was 1 for most of the basins, with exception of Maule, Itata and Biobío (due to the presence of waterfalls). Despite of having two natural barriers, the Maule showed the highest LF among all fragmented basins in this scenario (0.995), because both waterfalls are located in the upper reaches of the basin. In the current (2018) scenario the

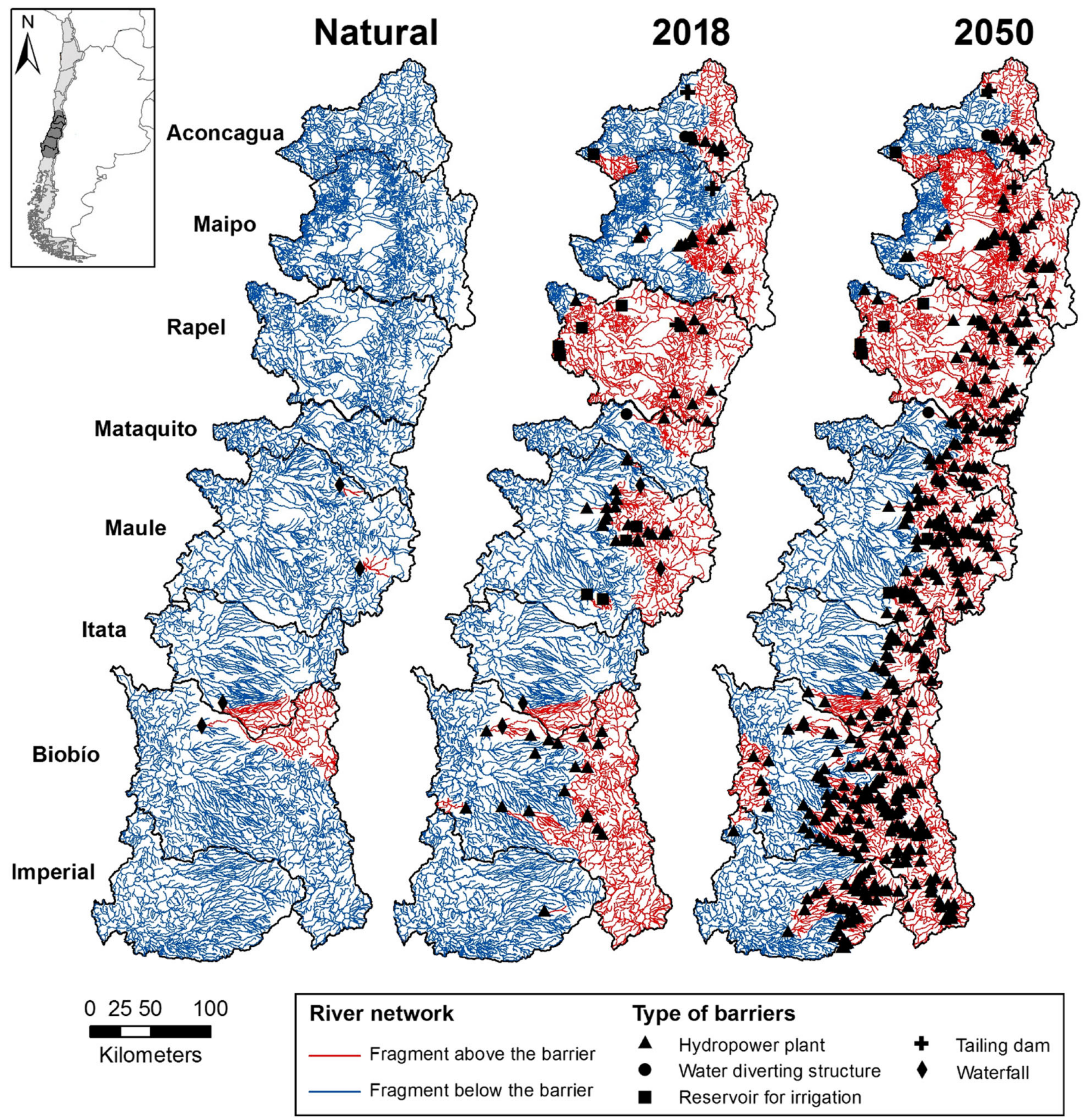

Fig. 4 Natural, current (2018) and future (2050) fragmentation scenarios of analysed river basins

highest LF value was observed for the Imperial and Itata basins (Table 3). The lowest LF value was found for the Rapel (0.651), and Biobío (0.706). In all basins except Rapel, the longest fragments correspond to those that are downstream of all barriers (Fig. 4). In the future (2050) scenario LF value decreased in all basins except Aconcagua and Maule (Table 3). Maipo basin was characterised by the highest decrease that resulted in the lowest LF value among all basins (0.410).

A total of 80 barriers of anthropogenic origin are present in the current (2018) scenario. Of these, 64 correspond to hydroepower plants, 9 to reservoirs for irrigation, 4 to tailing dams, and 3 to irrigation water diverting structures. The majority of barriers in the current (2018) scenario are hydropower plants (76%; Fig. 5), that are concentrated in the upper reaches of each basin at the piedmont of the Andes (Fig. 4). This pattern is consistent in all basins with the exception of Rapel which is characterised by an old barrier in its

Table 3 Metrics of fragmentation for each of the studied river network in the three analysed scenarios

Basin	Number of barriers (N)			Fragmentation index (FI)			Longest Fragment (LF)		
	Natural	2018	2050	Natural	2018	2050	Natural	2018	2050
Aconcagua	0	10	14	0	0.350	0.406	1	0.768	0.768
Maipo	0	13	33	0	0.393	0.786	1	0.729	0.410
Rapel	0	14	46	0	0.463	0.752	1	0.651	0.540
Mataquito	0	2	36	0	0.080	0.548	1	0.782	0.773
Maule	2	24	89	0.006	0.361	0.681	0.995	0.750	0.750
Itata	1	1	38	0.077	0.044	0.481	0.872	0.872	0.805
Biobío	1	19	158	0.050	0.436	0.936	0.776	0.706	0.668
Imperial	0	1	47	0	0.002	0.381	1	0.995	0.781

lower reaches (Rapel hydroelectric power station constructed in 1968). In the future (2050) scenario, similar pattern is observed, but the number of barriers fragmenting the upper Itata, Imperial, Mataquito, and Biobío increases. Furthermore, the number of barriers in the middle and lower reaches of the Biobío and Maipo are also expected to increase substantially by 2050 (Fig. 4).

Most of the barriers in the current (2018) scenario are placed in river reaches with Strahler order 4 (26 cases, of which 19 correspond to hydropower plants; Fig. 6). Furthermore, rivers with Strahler orders 6 and 7 are characterised by the lowest number of barriers (Fig. 6). In the future (2050) scenario, the number of barriers increased in all orders, with the exception of order 6. The highest increase was observed for reaches with Strahler orders 1 and 2 with 88 and 116 barriers, respectively (Fig. 6).

Rapel and Maipo basins have undergone the greatest change from the natural to the current (2018) scenario (Fig. 7). Biobío and Maipo are expected to undergo the greatest changes from the current (2018) to the future (2050) scenario, followed by Itata, and Mataquito (Fig. 7). Aconcagua and Imperial basins are expected to undergo less changes (Fig. 7).

Case study on configuration of potential hydropower plants in the Biobío basin showed that placement of new barriers in tributaries of the upper basin and upper part of the river mainstem caused the lowest increase of the FI and maintained the highest values of LF (Fig. 8d). Furthermore, compared to other scenarios, these configurations maximise the use of hydropower potential and at the same time are expected to maintain connectivity among populations of native fish (Fig. 8). In contrary, placement of new barriers in tributaries of the lower basins is expected to generate less hydropower and directly affect native fish populations of all analysed species (Fig. 8c).

Discussion

Already high current level of fragmentation of Chilean Andean rivers is expected to substantially increase in near future. As an effect of governmental strategy of encouragement of development of small hydropower dams as non-conventional renewable energy sources [26], the fastest increase of fragmentation is expected to occur in small and medium rivers (Strahler order 1, 2 and 3). This pattern also follows international trends of establishment of barrier in smaller basins [14]. Even though

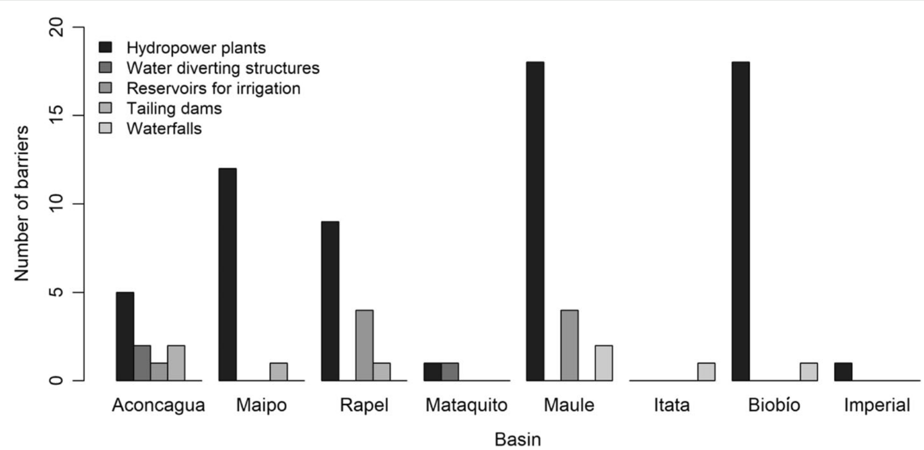

Fig. 5 Distribution of different types of barriers across basins in the current fragmentation scenario (2018)

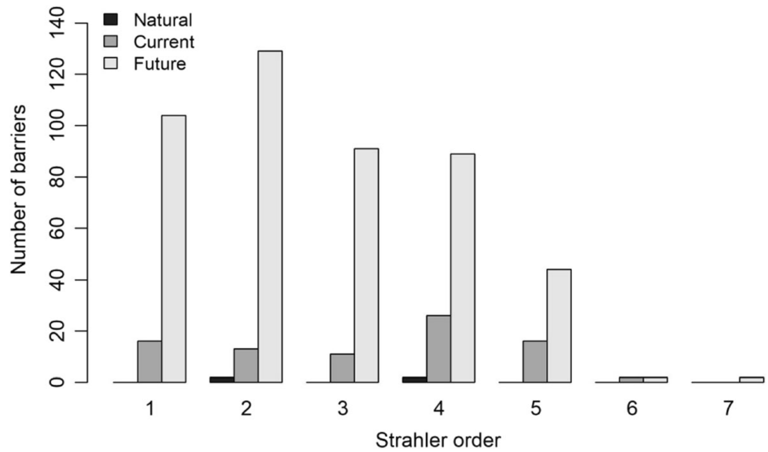

Fig. 6 Total number of barriers in the natural, current (2018) and future (2050) fragmentation scenarios across Strahler orders

hydropower development in Chile has its origins at the end of the eighteenth century, national electricity development plan started only in 1943 giving the beginning of construction of large hydropower plants. In line with this plan the number of large dams started to increase with 64 dams constructed up to 2018. Compared to the 'current' scenario (2018), in near future (2050) we expect rapid acceleration of construction of new hydropower plants with 437 projects with generation capacity higher than 3 MW in central Chilean basins. This implies 6.8-fold increase in number of barriers and corresponds to reduction of on average 12% of the longest fragments. The future scenario evaluated here, contemplates only hydropower dams. Other anthropogenic water resource related developments such as irrigation structures and tailing dams, may cause further increase of fragmentation. For example, new irrigation reservoirs are needed for growing agriculture and an increase of 57% (to reach 1.7 million hectares) in irrigated area in central Chile is already expected by 2022 [42]. Establishment of these new barriers is expected to have impact on functioning of Andean rivers of central Chile. We expect disturbance of sediment and woody debris transport at the basin scale and in multiple basins [5, 43] as well as significant changes in flow and thermal regimes [44, 45]. Therefore, barriers may affect the integrity of these river systems and alter their environmental conditions, and as a consequence impact their biodiversity and resistance to other environmental stressors [3, 7, 46].

Future changes in connectivity (increase of fragmentation) are expected to occur in parallel with other anthropogenic stressors. According to climate change predictions, higher temperatures, reduced precipitation and increased evaporation is expected in central Chile within upcoming decades [47]. For example, Pino et al. [48] estimated reduction of precipitation in central Chile by 20–30% in 2070; this reduction is expected to augment direct changes in connectivity on ecological

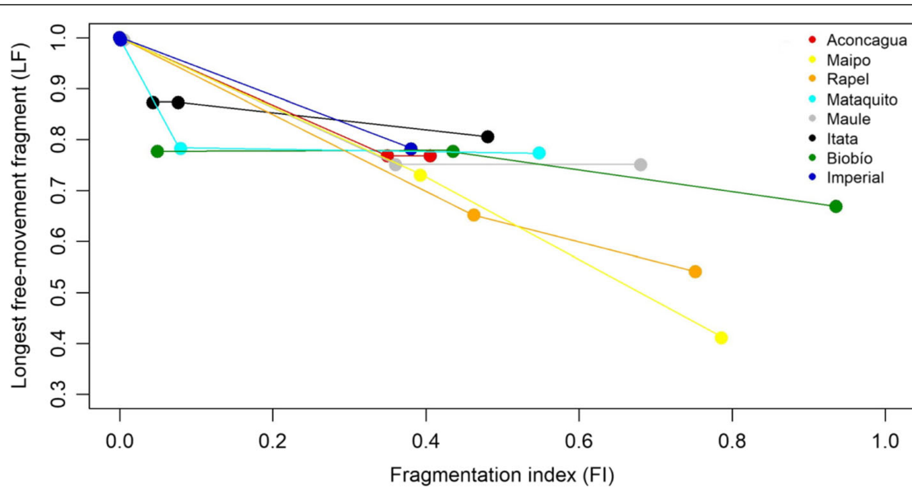

Fig. 7 Changes in fragmentation of analysed basins from the 'natural' to current (2018) and from current (2018) to future (2050) scenarios

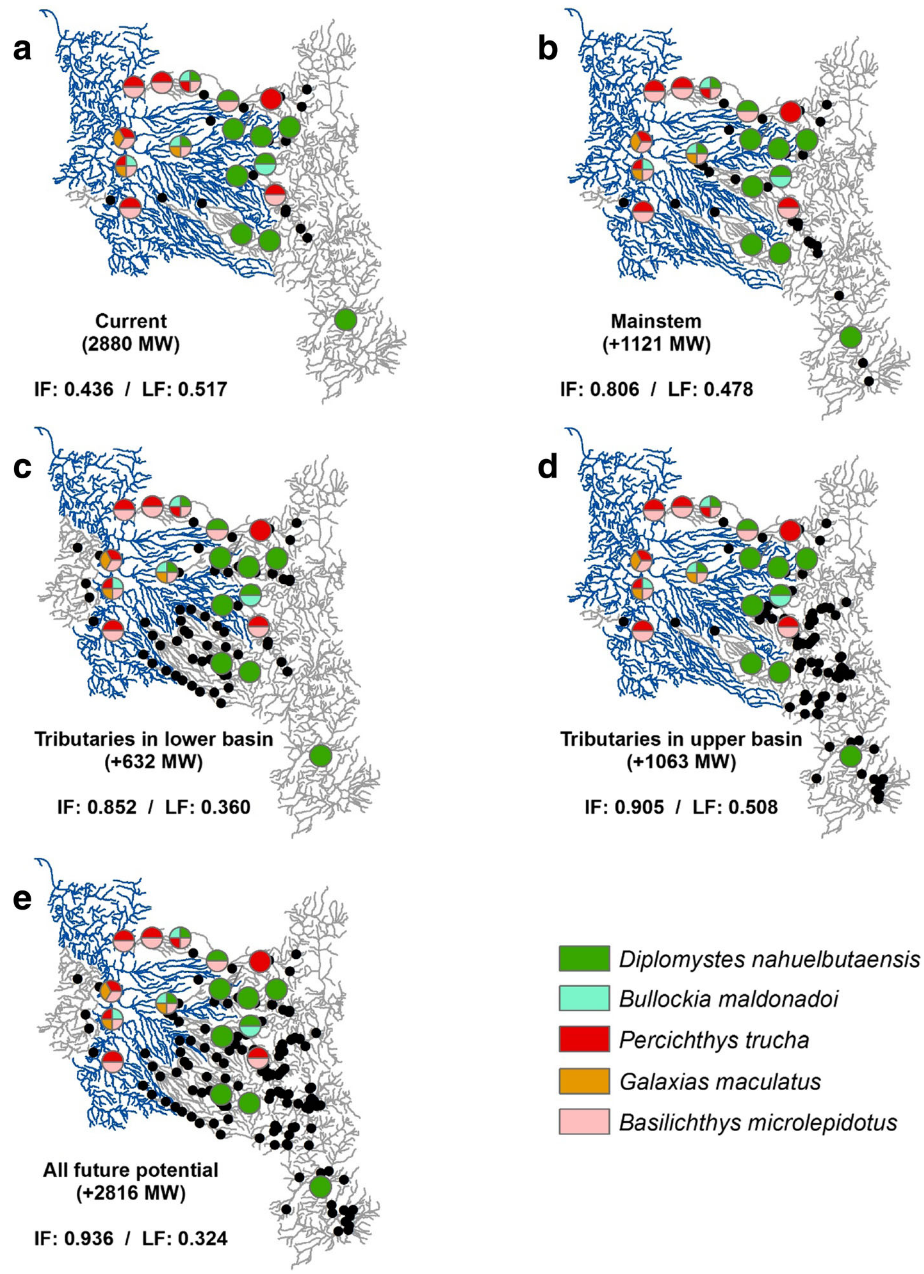

Fig. 8 Configurations of planning optimization for future hydropower plants on Biobío river network and distribution the five native fish species of high conservation value. Each configuration (**a** - **e**) show impacted (gray) and non-impacted (blue) fragments of the basin according to current and future hydropower plants locations (black dots). Furthermore the hydropower potential and values of corresponding fragmentation indices are indicated. The current distribution (based on presence /absence data) of native freshwater fishes was described using pie charts

function of these river systems. Furthermore, fragmentation and climate change in central Chile will work in concert with other anthropogenic stressors such as land-use changes and pollution as well as increasing demand of water for irrigation as well as industrial and domestic uses [42]. As such, two river basins that have the highest drinking and industry water demands, Maipo and Biobío [49], are also expected to undergo the highest connectivity loss due to hydropower development. Therefore, cumulative effects of multiple stressors are expected in these basins that require informed management actions in order to mitigate effects of these stressors on their ecological function and provision of ecosystem services.

Fragmentation assessment tool proposed here may be useful to monitor changes in connectivity as the main driver of riverine ecosystem function [50]. The FI incorporates explicitly the location of barriers trough Strahler orders and allows assessment of cumulative effects of barriers. Higher Strahler order reflects higher impact on basin level due to dendritic structure of river networks [1]. Furthermore, FI and LF can be used to assess the potential effects of fragmentation on fish communities of the entire basin independently of their life histories. This is different form indices proposed by [15] that require calculations of separate indices for diadromous and potamodromous fish species.

Addition or removal of hydropower plants in order to minimise the ecological effects of hydropower and restore or maintain connectivity of river networks is currently a major concern of river management and science (e.g., [51–54]). We show with our study case that similar hydropower potential could be harnessed with different hydropower plant configurations that can result in different effects on connectivity and ecology of river ecosystem. Fragmentation indices calculated for different scenarios showed severe changes in fragmentation level depending on configuration of hydropower plants within the basin [27]. Specifically for the Biobío River, hydropower output would be maximised and negative effects on fish communities minimised if new hydropower plants would be located in tributaries of the upper basin. This configuration maintains the connectivity of mainstem of the network that favours fish dispersal among non-impacted tributaries and therefore allows maintenance of fish metapopulations and metacommunities [46, 55]. Furthermore, it maximises the connectivity of tributaries in the lower basin that is inhabited by majority of native fish species and allows connection with marine habitats for diadromous species [56, 57].

Conclusions

Fragmentation of Chilean Andean river systems is expected to severely increase in near future, affecting their connectivity and ecological function as well as resilience to anthropogenic stressors. Indices proposed here allow quantification of this fragmentation and evaluation of different planning scenarios. Subsequently, as shown for the Biobío basin study case similar hydropower potential could be harnessed with different hydropower plant configurations that can have different impact on fish communities. As such, our results suggest that in Chilean Andean rivers new barriers should be prioritised in tributaries in the upper basin and already impacted fragments above existing barriers.

Abbreviations

FI: Fragmentation index; LF: Longest fragment

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Availability of data and materials

The data that support the results of this study were cited in "*River networks and barriers*" section of Methods and are available in the follow web sites:
http://www.geoportal.cl/visorgeoportal/ (Ministerio de Bienes Nacionales [35]).
http://sig.minenergia.cl/sig-minen/moduloCartografico/composer/ (Ministerio de Energía [36]).
http://walker.dgf.uchile.cl/Explorador/DAANC/ (Ministerio de Obras Públicas [37]).

Authors' contributions

GD, EH, KG, OL and JG designed the study and wrote the bases of manuscript; PA, BK, and OL contributed to design the indices; GD, PA and BK performed data analyses to modelled the fragmentation status of river basins in the study area; GD, KG and JG conducted the fieldwork to obtain fish data; GD, KG and EH contributed ideas and wrote the paper. All authors discussed the results and gave a final approval for publication.

Ethics approval and consent to participate

The capture of fishes for their identification and subsequent return to their environment were carried out under authorization of Servicio Nacional de Pesca y Acuicultura of Chile (SERNAPESCA/ Resolución exenta N°784).

Consent for publication

Non applicable.

Competing interests

The authors declare that they have no competing interests.

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Author details

[1]Departamento de Sistemas Acuáticos, Facultad de Ciencias Ambientales, Universidad de Concepción, P. O. Box. 160-C, Concepción, Chile. [2]Departamento de Ingeniería Ambiental, Facultad de Ciencias Ambientales, Universidad de Concepción, Concepción, Chile. [3]Departamento de Ecología, Facultad de Ciencias y Centro de Investigación en Biodiversidad y Ambientes Sustentables (CIBAS), Universidad Católica de la Santísima Concepción, Concepción, Chile. [4]Instituto de Ciencias Marinas y Limnológicas, Facultad de Ciencias, Universidad Austral de Chile, Valdivia, Chile. [5]Departamento de Ingeniería Civil, Facultad de Ingeniería, Universidad de Concepción, Concepción, Chile. [6]Departamento de Ingeniería Matemática, Facultad de Ciencias Físicas y Matemáticas, Universidad de Concepción, Concepción, Chile. [7]Centro de Ciencias Ambientales EULA, Universidad de Concepción, Concepción, Chile.

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