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Hydropower development, riverine connectivity and non-sport fish species: Criteria for hydraulic design of fishways

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Abstract

Hydropower barriers are among the most conspicuous anthropogenic alterations to natural riverine connectivity, resulting in species-specific effects linked to dispersal abilities, especially swimming performance. They may present a particular problem for small-bodied ‘non-sport fish’, such as those that characterize the freshwater communities of temperate regions in the Southern Hemisphere. Recent studies have suggested that nature-like fishways could ensure passage of diverse fish assemblages through hydropower barriers. Through experiments performed in a swim tunnel, we present, for the first time, fishway design criteria for two non-sport species endemic to Chile, a country experiencing rapid hydropower development. Incremental velocity tests showed that *Cheirodon galusdae* and juveniles of *Basilichthys microlepidotus* were capable of very similar standardized critical swimming speeds of 69.7 and 69.6 cm s⁻¹ respectively. When expressed in units of body lengths, *C. galusdae* was capable of very high critical speeds of 16.2 bl s⁻¹, whereas for *B. microlepidotus* this was 7.6 bl s⁻¹. However, fixed velocity tests revealed that the swimming endurance of the latter species was slightly higher. Dimensionless analysis showed a clear relationship between fatigue time and fish Froude number, similar to that already described for subcarangiforms. Based on these results we present fishway design curves indicating a transition from sustained to prolonged swimming at a fishway length of 15 m. Our results show that the swimming capacity of these species is well-suited to the mean flow velocity field described for nature-like fishways. However, more work is required to understand the effects of turbulence on the passage of non-sport species.

Keywords: River fragmentation, small body size fish, Multispecies fish-passes, Swimming capacity.

INTRODUCTION

Alterations to natural riverine connectivity have strong implications for fish population processes and community structure (Peres-Neto and Cumming, 2010; Webb and Padgham, 2013). Loss of physical connectivity is presumed to be one of the most generalized and important human induced alterations in riverine ecosystems, and it is frequently perceived as one of the main causes in the decline of freshwater fish species (Branco *et al.*, 2012). Intermittent stream connections as well as permanent features such as large waterfalls are natural barriers (Roberts *et al.*, 2013), but hydroelectric dams are among the most conspicuous anthropogenic barriers affecting riverine connectivity (Morita and Yamamoto, 2002). These barriers result in species-specific effects based on dispersal abilities.

‘Non-sport fish’ is a term used to describe freshwater species with small body size (< 150 mm total length when adults), which is the case for most native species in temperate regions of the Southern Hemisphere (see e.g. Boubée *et al.*, 1999, for New Zealand species and Link and Habit, 2015, for Chilean species). Due to their small body size, they are generally not commercially important, but several are endemics and have high conservation value (Habit *et al.*, 2006). Independently of their size, riverine fish species depend on connectivity along river systems to complete their life cycle and maintain genetic diversity and gene flow. Typically non-sport fish do not present a distinctive migratory behavior and are expected to have weaker swimming abilities than larger species (Belwood and Fisher, 2001). Accordingly, they may not suffer consequences of altered connectivity as severe as large diadromous species because they might be able to fulfill their life cycle at the river reach scale. However, over a long time period, habitat fragmentation could drive extinction of some species, due to loss of genetic diversity leading to a decline of fitness (Thomas, 2014). Indeed, in the absence of physical barriers non-migratory species can display surprisingly extensive gene flow patterns (Roberts *et al.*, 2013) and idiosyncratic genetic diversity and gene flow in the same river (Victoriano *et al.*, 2012). Therefore, fragmentation due to dams could have a large impact on these endemic non-sport species, which has not been well studied.

Besides translocation, the technical alternative for mitigation of fragmentation caused by hydropower dams, and thus for diminishing losses in riverine connectivity, is the construction of fish passes or ‘fishways’. With few exceptions work has been focused on ecohydraulic design criteria for sport fish species of the Northern Hemisphere, particularly salmonids (e.g. Brett and Glass, 1973; Taylor and Foote, 1991; Booth *et al.*, 1997; see Roscoe and Hinch, 2010, for a review). Equivalent information is scarce or non-existent for

most of the non-sport freshwater fish species, with some exceptions for galaxiids in New Zealand (Boubeé *et al.*, 1999; Nikora *et al.*, 2003; Baker and Boubeé, 2006; Plew *et al.*, 2007; Doehring *et al.*, 2011; Doehring *et al.*, 2012).

The hydraulic design of fish passes requires basic information on fish swimming abilities. Important parameters are related to swimming modes (Brett, 1964; Brett, 1967; Beamish, 1978; Hammer, 1995; Drucker, 1996; Sfakiotakis *et al.*, 1999), endurance (Brett, 1964; Brett, 1967; Beamish, 1978; Jones *et al.*, 1974; Videler and Wardle, 1991; Hammer, 1995), turbulence effects (Nikora *et al.*, 2003; Lupandin, 2005; Liao, 2007; Lacey *et al.*, 2012), and behavior (Plew *et al.*, 2007; Russon and Kemp, 2011). Swimming performance is especially important in determining when velocities are likely to exceed the endurance (e.g. for culverts) or burst (e.g. for orifice and weir fish ladders) swimming speeds (Russon and Kemp, 2011). In particular, the fatigue or critical swimming speed (Brett, 1964) corresponds to the velocity at which oxygen consumption is maximum, thus being a measure of the maximum aerobic capacity of fish (Hammer, 1995). The critical swimming speed is determined through the incremental velocity test (Brett 1964; Brett, 1967; Beamish 1978). Though a number of internal and external factors (e.g. population and body size, season and temperature, sex, water quality, light and food availability) affect the critical swimming speed, making the intra- and inter- specific comparison far from straightforward (Hammer, 1995), it is a standard approach for assessing the swimming capabilities of fish (Plaut, 2001; Farrel, 2008; Tudorache *et al.*, 2013; Gui *et al.*, 2014).

Without reference to other biological criteria, the use of critical swimming speed for fishway design rests on assumptions regarding swimming performance. For a more complete characterization of swimming ability, fish endurance curves can be fitted using the fixed velocity method (Brett, 1964; Beamish, 1978). In fishway design it is common to use endurance curves to gather specific information on how long (endurance times) and how far (swimming distances) a particular fish can swim against given water velocities (Katopodis, 1992). Katopodis (1994) developed the dimensionless endurance curves for fishway design for anguilliform and subcarangiform species.

The EU Water Framework Directive [WFD; 2000/60/EC] has advanced interest in progressing the development of fish passage criteria for multiple species throughout their life-history (Russon and Kemp, 2011). Consequently, over the last decade, design criteria have started to change towards consideration of requirements of target species for effective multi-species fish passage provision (Baker and Boubeé, 2006; Fould and Lucas, 2013). Additionally, an ecosystem approach has led to the development of nature-like fish passes (Baki *et al.*, 2014). Their main objective is to provide suitable passage for all biota living in a waterbody (Katopodis *et al.*, 2001). Recently, nature-like fish passes have been

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3 recognized as economically and ecologically viable alternatives to traditional engineered
4 fish passes (e.g., pool and weir, vertical slot, or Denil fish passes), and have attracted
5 considerable interest. They are typically constructed with naturally occurring materials such
6 as combinations of gravel, rocks, boulders, bamboo, and wood (Katopodis and Williams,
7 2012).

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11 Considering the urgent need for design of multi-species, nature-like fish passes for
12 non-sport fish, in this study we analyze swimming abilities of two endemic species to
13 Chile, *Cheirodon galusdae* (Eidenmann 1928) and juveniles of *Basilichthys microlepidotus*
14 (Jenyns 1841), both <120 mm total length. With this research we answer the question of
15 whether existing design guidelines for nature-like fishways (e.g. Katopodis, 1992;
16 FAO/DVWK, 2002; USBR, 2007) are applicable to non-sport fishes, i.e. are their
17 swimming abilities similar to salmonids and galaxiids? To what extent are any arising
18 differences important for fishway design? Consequently, we present information on both
19 critical swimming speed and endurance, and compare them with available information.
20 Finally, the implications for fishway design are illustrated through design curves for
21 maximum allowable flow velocity in a fish ramp for different lengths.
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29 MATERIALS AND METHODS

30 Studied species

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32 The studied species are endemic to the Chilean ichthyogeographic province (*sensu*
33 Dyer, 2000) located in the Central-South zone of the country, between 28° and 41° Lat. S.
34 The same geographic area is classified as a biodiversity hotspot (Myers *et al.*, 2000) and is
35 under high pressure for hydropower development with about 1000 new expected projects of
36 small hydropower plants (Ministerio de Energía 2015). Typically these dams are up to ca.
37 3–5 m high and divert discharges in the order of several cubic meters per second, usually
38 around 1 m³/s. Even when these dams do not have regulation capacity, they impound water
39 upstream and disrupt connectivity for small body size fish (Link and Habit, 2015). The
40 region comprises 23 main Andean watersheds (from the Huasco to the Bueno River with
41 watershed between 500 and 24.500 km²) and several small watersheds of rivers with their
42 origin in the coastal mountain range and streams of the Chiloé Island (Figure 1).
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51 *Cheirodon galusdae* inhabits at the piedmont of the Andes and Central Valley from
52 35 to 39° Lat. S. (Dyer, 2000). Maximum body size is 90 mm when adult and swimming
53 mode is subcarangiform. *Basilichthys microlepidotus* inhabits at the piedmont of the Andes
54 and Central Valley from 21 to 40° Lat. S. (Véliz *et al.*, 2012). Maximum body size is 120
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mm for juveniles and 300 mm when adults. Swimming mode is carangiform (Link and Habit, 2015). Conservation status of both species is vulnerable (Vila and Habit, 2015).

Capture and maintenance

Fish were collected from the Itata River using a backpack electroshocker (Smith-Root LR24, Vancouver, WA, USA) and seine net (2-mm mesh). All collected fish were transported to glass aquariums at the Hydraulics and Environmental Engineering Laboratory of the University of Concepción. To avoid mortality, guideline for fish transportation and successful maintenance in captivity of Chilean native fish was follow (Sobenes et al. 2012). Fish were kept for at least 15 days before experiments. Fish were fed *ad libitum* with live prey (macroinvertebrates from streams and *Enchitrea* sp., *Tenebrio molitor*, and *Eisenia foetida*) three or four times a week according to Sobenes *et al.* (2012) and García *et al.* (2012). Following Jobling (1982) feeding was interrupted 48 h before each experiment. Water temperature was kept stable at 17±1°C for 1 week before the experiment.

A total of 198 individuals (93 *C. galusdae* and 105 *B. microlepidotus*) of different body length classes were tested (see supplementary material). All individuals of *C. galusdae* were adults, while all *B. microlepidotus* were only juveniles due to body length restrictions of the laboratory equipment. A total of 70 individuals were used for determination of critical swimming speed (31 *C. galusdae* and 39 *B. microlepidotus*) and 128 individuals for determination of endurance curves (62 *C. galusdae* and 66 *B. microlepidotus*). For the critical swimming speed and endurance tests respectively, the mean (±SD) total body length was 44.0 (±9.0) mm and 42.4 (±4.3) mm for *C. galusdae* and 81.0 (±0.1) mm and 84.6 (±9.1) mm for *B. microlepidotus*.

Experimental installation and protocols

Experiments were conducted in a swimming tunnel (Loligo System SW10050; Figure 2). Discharge was controlled by a variable frequency drive, and temperature was kept constant using a chiller (Resun Mini20).

Determination of critical swimming speed

Critical swimming speeds were determined following the incremental velocity test (Brett, 1964; Brett, 1967; Beamish, 1978; Hammer, 1995; Plaut, 2001). Individuals were acclimated at a slow velocity of 0.5 bl s⁻¹ for 2 hours. Flow velocity was maintained for 600 s and incremented in steps of 1.0 bl s⁻¹ until fatigue. The critical swimming speed was computed as (Brett, 1964):

$$U_c^i = U_f + \frac{t_f}{\Delta t} \Delta U \quad (1)$$

where U_c^i is the critical velocity achieved by the i^{th} fish, U_f is the highest velocity maintained, t_f is the time to fatigue at the highest velocity, Δt is the time increment (600 s), and ΔU is the velocity increment (1.0 bl s^{-1}).

Because U_c^i varies significantly among individuals, it is usual to characterize the swimming capacity of a species through the mean critical velocity (e.g. Mateus *et al.*, 2008; Castro *et al.*, 2010):

$$\overline{U_c} = \frac{1}{n} \sum_i^n U_c^i \quad (2)$$

where n is the total number of individuals.

For a standardization of the swimming capacity according to the body length, Smit *et al.* (1971) proposed the standard critical velocity:

$$U_c^* = \frac{1}{n} \sqrt{\frac{1}{n} \sum_i^n L_i \frac{(U_c^i)^2}{L_i}} \quad (3)$$

where L_i is the total body length of the i -fish. U_c^* allows comparison between species (Hammer, 1995).

Determination of endurance curves

Endurance curves were determined following the fixed velocity test (Brett 1964; Brett, 1967; Beamish, 1978; Jones *et al.*, 1974; Adams *et al.*, 1999) in which the swimming performance of the fish is measured as time to fatigue for increments of flow velocity. Individuals were acclimated at a very slow velocity of 0.5 bl s^{-1} for 1.5 hours. Flow velocity was kept constant until fatigue. For each species, 12 to 13 different velocities between 17 and 128 cm s^{-1} were tested. Fish were considered fatigued when, despite attempts, they remained impinged for more than 10 seconds on the net.

Katopodis (1994) analyzed swimming performance of several fish species with variables representing the fish Froude number and the standardized fatigue time, finding different patterns for carangiforms and anguilliforms. The variables are:

$$F_f = \frac{U_f}{\sqrt{gL}} \tag{4}$$

$$t^* = t \sqrt{\frac{g}{L}} \tag{5}$$

where U_f is the section averaged flow velocity, g is acceleration due to gravity, L is the total body length, and t is time to fatigue.

Fishways design curves

Design curves were produced following Peake *et al.* (1997):

$$U_f = U_s - \frac{D}{t} \tag{6}$$

where U_s is the swimming speed of the fish, and D is the fishway length. Maximum allowable flow velocity in the fishway is:

$$U_{f,max} = \max \left(U_s - \frac{D}{t} \right) \tag{7}$$

RESULTS

Critical swimming speed

U_c^i was highly variable, ranging from 38.3 to 96.8 cm s⁻¹ for *C. galusdae* and from 28.2 to 140.0 cm s⁻¹ for *B. microlepidotus*. The standardized critical velocity (Hammer, 1995) was $U_c^* = 69.7$ and 69.6 cm s⁻¹, for *C. galusdae* and *B. microlepidotus* respectively (Figure 3a). When plotted in dimensions of bl s⁻¹, standarized critical speeds exhibit less variability with body length. In this case, $U_c^* = 16.2$ and 7.6 bl s⁻¹ for *C. galusdae* and *B. microlepidotus* respectively. The correlation with fish length is $U_c^* = -1.65L + 23.25$ ($R^2 = 0.14$,

p<0.04) for *C. galusdae* and $U_c^* = 1.25L - 2.44$ ($R^2 = 0.29$, p<0.0004) for *B. microlepidotus* (Figure 3b). Negligible differences were obtained using the mean critical velocity. \overline{U}_c was 69.4 and 70.1 cm s⁻¹, or 15.9 and 7.7 bl s⁻¹, for *C. galusdae* and *B. microlepidotus*, respectively.

Endurance

Endurance of *B. microlepidotus* was slightly higher than *C. galusdae*, but the endurance of both species was similar to that of *O. mykiss*, *G. maculatus* and *G. vulgaris* (Figure 4). Sustained swimming for *B. microlepidotus* covers a wider range of velocities (up to 52.3 cm s⁻¹) than *C. galusdae* (up to 46.1 cm s⁻¹). Endurance decreases at very similar rates with velocity for both species.

Figure 5 shows dimensionless endurance curves for *C. galusdae* and *B. microlepidotus*, including patterns described for anguilliforms and carangiforms (Katopodis, 1994). Data points collapse showing a clear relationship between standardized fatigue time t^* and fish Froude number F_f . The slope of the tendency line for both species is similar to that found by Katopodis (1994) for subcarangiform species, indicating that endurance of carangiforms (i.e.: *B. microlepidotus*) and subcarangiforms vary in similar form with the fish Froude number.

3.3 Fishway design curves

Maximum allowable flow velocities for passage of fishways with lengths from 5 to 100 m equate to 87.8 to 60.1 cm s⁻¹ for *C. galusdae*, and 90.5 to 64.5 cm s⁻¹ for *B. microlepidotus* (Figure 6). The latter could withstand higher flow velocities than *C. galusdae*. Maximum allowable flow velocities for both species decreased with fishway length when considering average endurance. However, when considering the weakest performing individuals, curves exhibit a change in slope at a fishway length of 15 m, indicating a change from sustained to prolonged swimming mode (Figure 6).

DISCUSSION

In contrast to what it was expected, standardized critical velocities of the studied non-sport fish species (69.7 cm s⁻¹ for *C. galusdae* and 69.6 cm s⁻¹ for *B. microlepidotus*) resulted in the same range and even higher than those reported for salmonids (e.g. *O. mykiss*, with 36.1–41.9 cm s⁻¹ for lengths of 890–950 mm; Bestgen *et al.*, 2010). Also they were similar to those reported for other small size body species of the Southern Hemisphere like *G. maculatus* and *G. vulgaris* (galaxiids) in New Zealand. Moreover, the Brazilian

characin *Bryconamericus stramineus* Eigenmann, 1908, similar to the native characin from Chile, *C. galusdae*, presented a critical velocity of 51 cm s^{-1} for individuals which have just reached sexual maturity at 590 mm total length (Castro *et al.*, 2010). As a result, when velocities are expressed in body lengths per second (bl s^{-1}), *C. galusdae* exhibited a very high critical speed of 16.2 bl s^{-1} , comparable with burst velocities of fast swimming salmonid like *Stenodus nelma* (Pallas 1773) (13.6 bl s^{-1} , Jones *et al.*, 1974). Similarly, available information on swimming performance for galaxiids suggest that this non-sport species appears capable of maximum swimming speeds of the order 10 bl s^{-1} (Mitchell, 1989; Nikora *et al.*, 2003; Plew *et al.*, 2007). However, these results are consistent with the described fish physiology, since the relative speed in body lengths per second is almost invariably higher in smaller species (Bainbridge, 1958; Wardle, 1975; Belwood and Fisher, 2001). This was demonstrated also with reef fish larvae, which achieved swimming speeds as higher as 49 bl s^{-1} (Belwood and Fisher, 2001).

Our results clearly show that swimming capacities of the studied species are well-suited with the mean flow velocity field described for nature-like fish ramps designed for salmonids. However, other variables besides current velocities like turbulence are relevant in fishway design. Bretón *et al.* (2013), as well as Baki *et al.* (2014 and 2015), analyzed the flow field and turbulence in a typical salmonid fish ramp. Their results showed that flow velocities occurring in the fishway would allow the passage of *C. galusdae* adults and *B. microlepidotus* juveniles. Therefore, it is expected that nature-like fish ramps represent a viable alternative for mitigation of habitat fragmentation of non-sport fish species, like the studied species. However, as both species inhabit the water column (Link and Habit, 2015) further research is needed to generalize the feasibility of nature-like fish ramps as multi-species fishway for other non-sport fishes with different habitat use. For example, Gischke (2014) observed that the benthic native catfish *Trichomycterus areolatus* (Vallenciennes 1840) presented an inhibited rheotaxis and performs sprints, preferentially for flow velocity equal 1.0 bl s^{-1} . Similarly, preliminary analysis using the native Chilean darter *Percilia gillissi* Girard 1855, revealed a different behavior, since it remains in the same position on the bottom using pectoral fins, instead of increasing its swimming velocity with the flow.

Even though this study clearly shows that the mean flow field occurring in a nature-like fish-ramp is compatible with the swimming capacity of adults of *C. galusdae* and juveniles of *B. microlepidotus*, corresponding turbulence might be an issue for their passage (Lacey *et al.*, 2012; Wilkes *et al.*, 2013). Instantaneous velocities in most technical fish passes, traditionally designed for sport fish species capable of very high burst speeds (*e.g.* up to 4.13 m s^{-1} for *Salmo salar* Linnaeus, 1758; Colavecchia *et al.*, 1998), are likely to exceed the burst speeds of the species studied. Furthermore, as non-sport fish are expected

to be smaller than wake vortices in a number of cases, the size and frequency of vortices are expected to significantly affect swimming abilities (e.g. Liao *et al.*, 2003; Liao 2007). Further research is needed to integrate effects of turbulence on swimming abilities of non-sport fish in fishway design, and to evaluate suitability of the nature-like fish ramp for provision of longitudinal river connectivity. This would also provide an opportunity to test the transferability of swimming performance measures from highly artificial laboratory conditions.

At a time when the world is experiencing a boom in the construction of hydropower dams due to global population growth, increasing electricity demand, the need to reduce greenhouse gas emissions, and the vast unrealized potential of renewable energy resources (Zarfl *et al.*, 2014, Zhou *et al.*, 2015), riverine connectivity arises as a very sensitive issue. Traditional fish passes, originally conceived for migratory sport fish species, and especially nature-like fish ramps appear to be suitable for provision of habitat connectivity for non-sport species.

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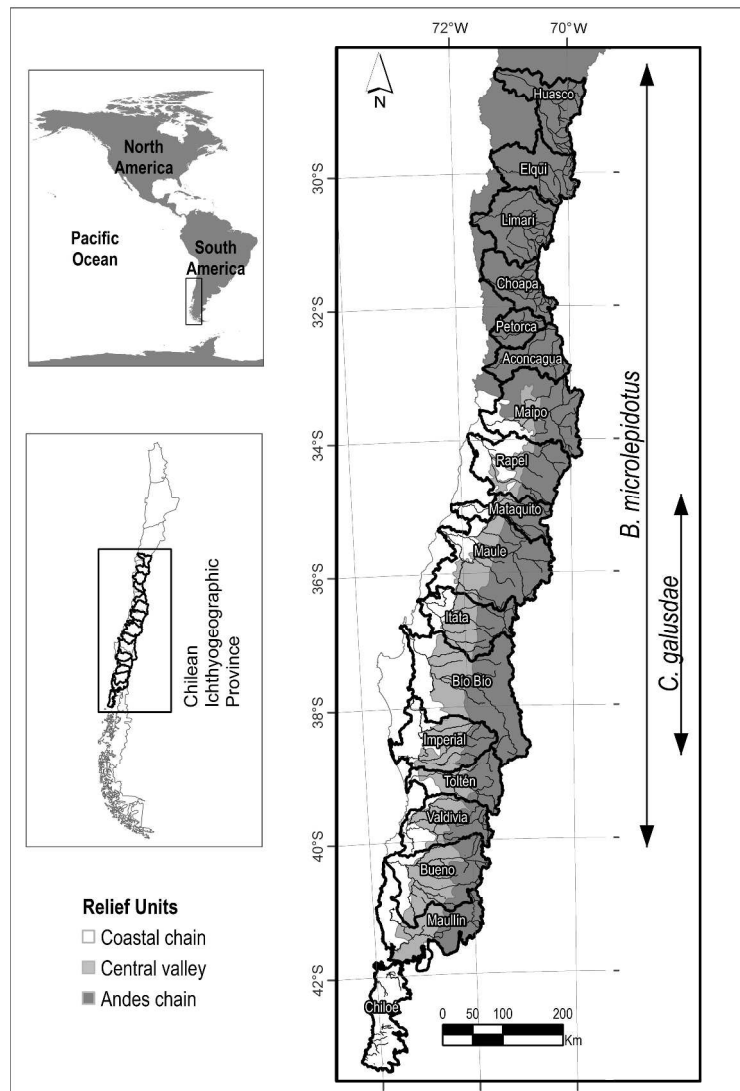
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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher’s web-site.



Distribution of the studied species in the Chilean ichthyogeographic province.
232x375mm (600 x 600 DPI)

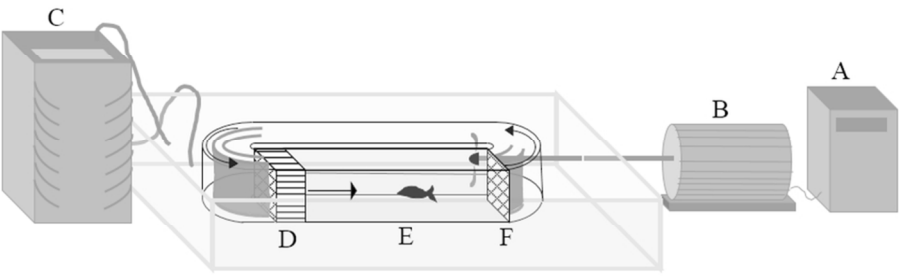


Figure 2. Variable frequency drive (A), pump (B), chiller (C), honeycomb matrix for flow alignment (D), swim chamber (E), and (F) net. 90x30mm (300 x 300 DPI)

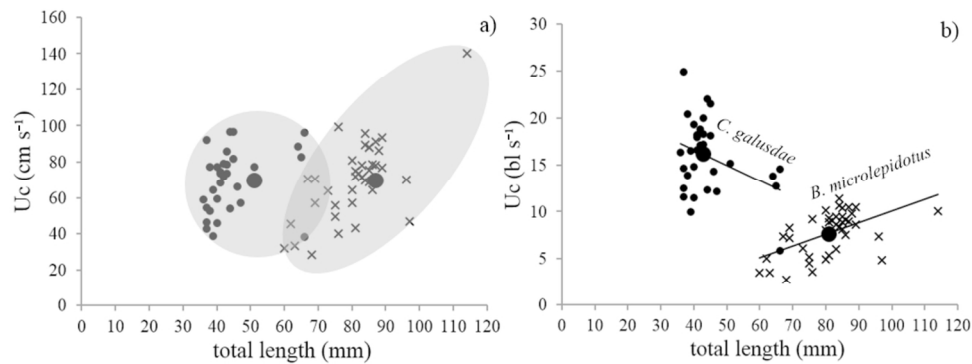


Figure 3. Critical swimming speed over total body length for *C. galusdae* and *B. microlepidotus*. a) in $[\text{cm s}^{-1}]$, and b) normalized by the body length in $[\text{bl s}^{-1}]$. The grey areas indicate the expected range of U_c for the different sizes and the large circles indicate the critical swimming speed for the species.

114x47mm (300 x 300 DPI)

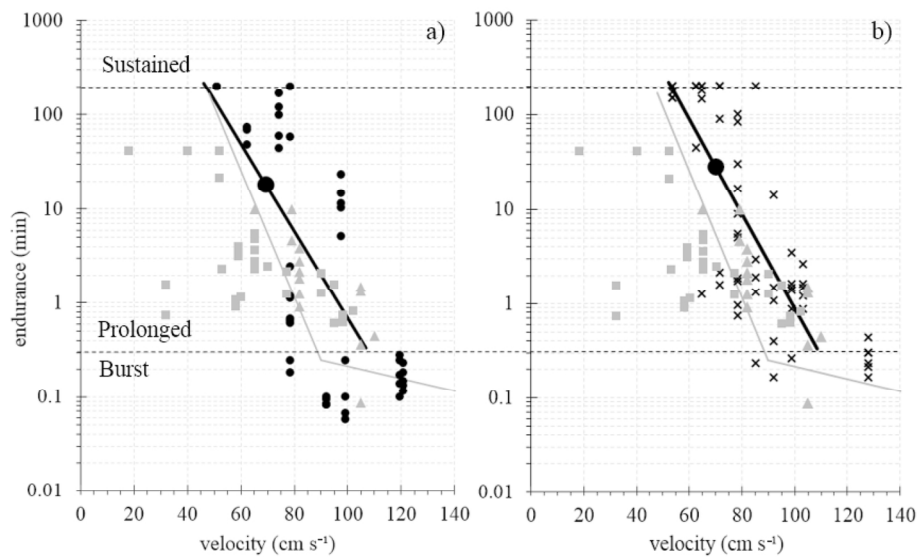


Figure 4. Endurance curves for (a) *C. galusdae* and (b) *B. microlepidotus*. Black lines correspond to the line of best fit. Large circles correspond to the critical velocity. For reference, curves are also shown for other species. The grey lines correspond to endurance of *O. mykiss* with total length of 70 mm (Boube , 1999), grey triangles to *G. maculatus* with a total length of 70 - 110 mm, and grey squares to *G. vulgaris* with a total length of 60 - 80 mm (Stevenson and Baker, 2009).

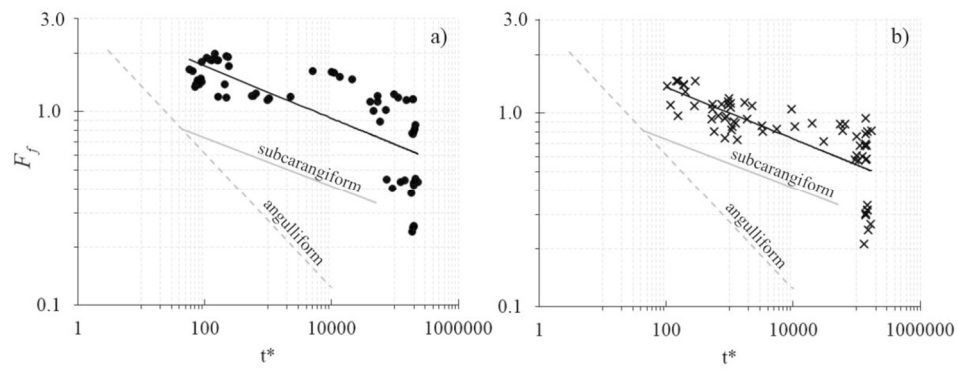


Figure 5. Normalized endurance curves for (a) *C. galusdae* and (b) *B. microlepidotus*. Grey lines are patterns for anguiliforms and subcarangiforms (Katopodis, 1994).
129x50mm (300 x 300 DPI)

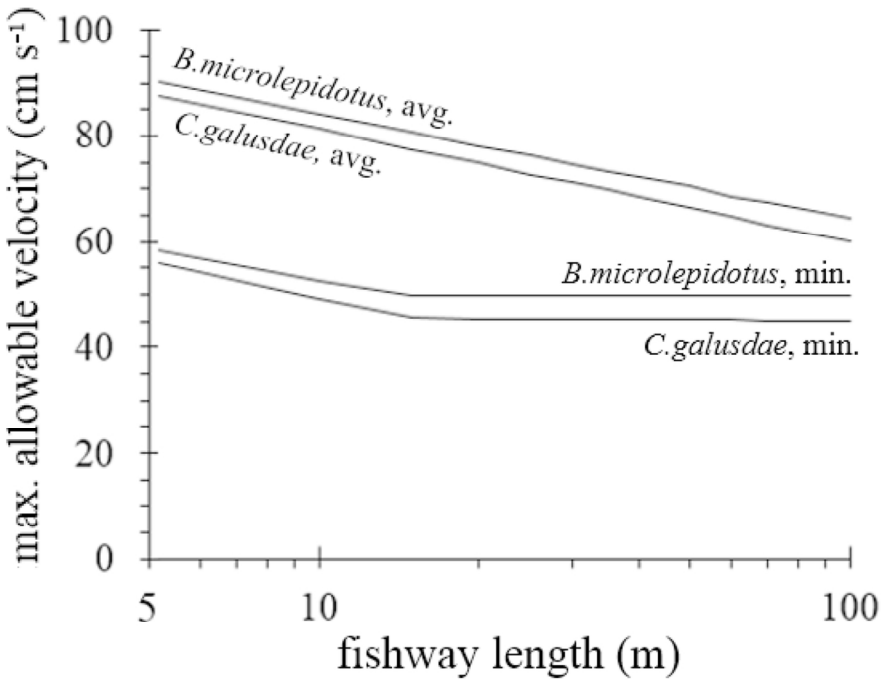


Figure 6. Maximum allowable flow velocity over fishway length computed with average (avg.) and minimum (min.) endurance capacities for *C. galusdae* and *B. microlepidotus*.
119x92mm (300 x 300 DPI)