PERMEABILITY OF SMALL WEIRS FOR UPSTREAM FISH PASSAGE

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RIVER RESTORATION AND MANAGEMENT

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Abstract

River fragmentation is a serious threat to the sustainability of fish populations. Although far more numerous than dams, the impact of small weirs on fish migration have received less attention, for being considered permeable to fish movements. Nevertheless, the presence of small weirs may cause successive losses of connectivity by partially or totally blocking migratory routes. Potamodromous cyprinids are particularly impacted due to their need of undergoing seasonal upstream migrations. The goal of this thesis was to assess the effects of small weirs, particularly broad-crested and low-head ramped weirs, which are the most frequent designs in Iberian watercourses, on behaviour and passage performance of potamodromous cyprinids. A field assessment was performed to understand how these obstacles may affect, in an otherwise non-impacted stream, the movements of cyprinids. I addition to this field study, laboratorial experiments were carried out in an indoor flume. In these experiments, the influence of key hydraulic parameters – plunge pool depth, waterfall height, and weir crest width, in the case of broad-crested weirs; ramp length, and slope, for low-head ramped weirs, on passage performance of fish was tested across a range of discharges. Iberian barbel (*Luciobarbus bocagei*) was selected as target species. Main results suggest that barbel may cease to migrate, when suitable habitats exist between barriers. Regarding broad-crested weirs, it was found that i) fish passage was inhibited by shallow plunge pool depths in association with high waterfall heights; ii) passage behavior was dependent on combinations of plunge pool depths and waterfall heights; and iii) the width of the crest influenced downstream passages but not upstream ones. For ramped weirs, i) negotiation was conditioned by the increase of slope and ramp length; and ii) retrofitting ramped weirs with natural substrates like cobbles may increase permeability to fish movements. These outcomes are useful to identify potential migration obstacles and to help design more permeable structures to fish movements.

Key-words: Ecohydraulics; river connectivity; potamodromous cyprinids species; migratory movements; small weirs.

Resumo

A fragmentação dos rios constitui uma séria ameaça à sustentabilidade das populações piscícolas. Embora os pequenos açudes sejam mais numerosos que as grandes obras hidráulicas, os seus impactes nos movimentos migratórios dos peixes têm recebido menos atenção, por serem considerados como estruturas permeáveis à movimentação. No entanto, a presença de pequenos açudes pode causar sucessivas perdas de conectividade, bloqueando parcial ou totalmente as rotas migratórias. As espécies ciprinícolas potamódromas são particularmente afetadas, devido à necessidade de realizarem migrações sazonais para montante. O objetivo desta tese foi estudar os efeitos dos pequenos açudes, mais concretamente dos açudes de faces verticais e dos açudes rampeados, por serem as tipologias de açudes mais frequentes nos cursos de água Ibéricos, no comportamento e desempenho natatório dos ciprinídeos potamódromos. Foi realizada uma avaliação de campo, num pequeno rio não impactado de outra forma, para entender como é que estes obstáculos podem afetar os movimentos dos ciprinídeos. Juntamente com este estudo de campo, foram realizados ensaios laboratoriais num canal. Nestes ensaios, foi testada a influência de parâmetros hidráulicos considerados preponderantes – profundidade de água a jusante do açude, queda a transpor, e comprimento da soleira, no caso dos açudes de faces verticais; comprimento da rampa, e inclinação, nos açudes rampeados, no desempenho de natação dos peixes, ao longo de uma variedade de caudais. O barbo-comum (*Luciobarbus bocagei*) foi selecionado como espécie-alvo. Os principais resultados sugerem que o barbo pode diminuir os seus movimentos migratórios, quando existem habitats adequados entre barreiras. No que diz respeito aos açudes de faces verticais, verificou-se que i) a capacidade de transposição foi inibida pela ocorrência de baixas profundidades de água a jusante do açude em associação com elevadas quedas de água a transpor; ii) o comportamento de passagem dependeu da combinação de profundidade de água a jusante com a queda de água a transpor; e iii) o comprimento da soleira influenciou as passagens para jusante, mas não as transposições para montante. Para os açudes rampeados, i) a transposição foi condicionada pelo aumento do comprimento da rampa, e da sua inclinação; e ii) a aplicação de substratos naturais, como pedras, pode aumentar a permeabilidade das rampas à movimentação dos peixes. Estes resultados são úteis para identificar os possíveis obstáculos à migração, e para ajudar a projetar e requalificar estruturas de forma a aumentar a sua transponibilidade para os peixes.

Palavras-chave: Ecohidráulica; Conectividade fluvial; espécies ciprinícolas potamódromas; movimentos migratórios; pequenos açudes.

Resumo Alargado

A perda da conectividade fluvial, principalmente na sua dimensão longitudinal, tem sido apontada como uma das principais ameaças à sustentabilidade das populações piscícolas. Durante as últimas décadas, a construção de infraestruturas hidráulicas, como barragens e pequenos aproveitamentos hidroelétricos (PAH), tem vindo a aumentar, devido à crescente promoção das energias renováveis e das necessidades de abastecimento de água para a agricultura, indústria e cidades. A fragmentação dos cursos de água, juntamente com a regularização de caudais imposta por essas infraestruturas, é indicada como principal causa de degradação dos habitats aquáticos, estimando-se que seja responsável por cerca de 48% das alterações no volume global dos rios, e por mais de 50% do declínio das espécies de peixes com estatuto de ameaçadas na Europa.

Indo ao encontro do estabelecido na Diretiva Quadro da Água (Directiva 2000/60/CE), vários estudos têm sido realizados para documentar os diversos impactes dessas infraestruturas hidráulicas nos ecossistemas ribeirinhos, e dessa forma encontrar soluções que possam colmatar ou minimizar os seus efeitos adversos, tais como a construção de dispositivos de passagem para peixes. Contudo, ao contrário do que acontece com os impactes das barragens e dos PAH, os impactes de pequenas obras hidráulicas nas comunidades piscícolas, como os impactes dos pequenos açudes (< 5 m de altura), têm recebido muito menos atenção, pois estas estruturas têm sido consideradas como pequenas barreiras que são a priori permeáveis à livre movimentação dos peixes. No entanto, até mesmo os pequenos açudes, que se estima serem 2-4 ordens de grandeza mais numerosos do que as barragens e os PAH, modificam a hidrodinâmica natural dos cursos de água, alterando a velocidade da corrente e as profundidades da água, tanto a montante como a jusante da estrutura, bem como formando desníveis, em alguns dos casos, que poderão ser eventualmente intransponíveis. Portanto, a presença de açudes ao longo dos cursos de água poderá provocar sucessivas perdas de conectividade, com consequências negativas para as populações piscícolas, principalmente para as que necessitam de efetuar migrações como as espécies diádromas e potamódromas.

Na Península Ibérica, as comunidades piscícolas são constituídas principalmente por espécies ciprinícolas potamódromas, das quais fazem parte um elevado número de endemismos atualmente ameaçados devido à perda de conectividade longitudinal. Estas espécies potamódromas, que são estritamente dulçaquícolas, apresentam padrões de mobilidade bem característicos, em que os principais movimentos migratórios de desova ocorrem principalmente durante a primavera e o início do verão. Tendo em conta as suas capacidades natatórias, quando comparados com os salmonídeos adultos, os ciprinídeos são normalmente considerados como espécies que apresentam uma moderada ou baixa capacidade de transposição de barreiras, devido ao seu limitado desempenho de natação, e pequena capacidade de salto. Assim, a permeabilidade dos pequenos açudes aos movimentos da fauna piscícola é altamente condicionada pelas condições locais e temporais, bem como pelas características das espécies presentes. Portanto, o efeito que estes obstáculos exercem sobre os movimentos migratórios dos peixes pode não estar apenas linearmente relacionado com o seu número (no caso dos rios Portugueses, estima-se que existam mais de 8000 açudes), mas depende intimamente das características físicas dos obstáculos, das condições hidrodinâmicas presentes nas proximidades, e das capacidades de natação dos peixes. Torna-se desta forma fundamental considerar a complexidade destas condicionantes e desenvolver mais estudos, particularmente para estas espécies com capacidades natatórias menos desenvolvidas.

Com os estudos realizados nesta tese, pretendeu-se avaliar a capacidade das espécies ciprinícolas potamódromas Ibéricas de transpor pequenos açudes. Para tal, o desempenho de transposição dos peixes, bem como o seu comportamento aquando da aproximação e transposição destes pequenos obstáculos, foram analisados afim de aumentar o conhecimento sobre estas espécies, que são frequentemente menos estudadas, e dessa forma poder i) identificar possíveis obstáculos à livre movimentação dos peixes, ii) compreender os problemas dos pequenos açudes existentes, e iii) sugerir medidas de requalificação que possam melhorar a permeabilidade destas estruturas aos movimentos dos ciprinídeos.

Inicialmente, realizou-se um estudo de campo no troço de montante do rio Alviela, considerando um segmento com 5.6 km de comprimento onde foram identificados apenas impactes resultantes da presença de barreiras físicas. O intuito deste estudo foi de catalogar as tipologias de açudes mais frequentes, bem como avaliar a influência desses obstáculos nos movimentos migratórios dos ciprinídeos, mais concretamente do barbo-comum (*Luciobarbus bocagei*). Assim, os açudes presentes no segmento selecionado foram identificados e caracterizados sazonalmente, em cinco épocas de amostragem desde a primavera de 2012 até ao verão de 2013, aplicando o Índice de Conectividade Fluvial (ICF), e os espécimes de barbo-comum, capturados com recurso à pesca elétrica, foram identificados com marcas VIE (Visible Implant Elastomer), usando um código resultante da combinação de três cores aplicadas em quatro diferentes partes do corpo do peixe, de forma a permitir o reconhecimento dos peixes capturados/recapturados, tendo em conta o local de captura, e a estação do ano. Os resultados deste estudo revelaram que as tipologias de açudes mais frequentes nestes cursos de água são os pequenos açudes de faces verticais, que apresentam a face de jusante vertical e que, portanto, geram uma queda, juntamente com os açudes rampeados, que não geram uma queda pois têm faces inclinadas, que os peixes poderão superar nadando. Em relação à movimentação dos espécimes, embora a classificação do ICF tenha sido pobre, principalmente durante a principal época de migração desta espécie, verificou-se que 11% dos indivíduos marcados deslocaram-se entre barreiras. No entanto, muitos preferiram não se deslocar, especialmente quando estavam presentes locais adequados para a desova. Assim, pode concluir-se que, quando existem habitats adequados entre barreiras, a presença destes obstáculos pode condicionar o comportamento migratório destas espécies, que em último caso poderão deixar de migrar.

Para além deste estudo de campo, esta tese teve uma forte componente de ensaios laboratoriais, desenvolvidos num canal experimental que se encontra nas instalações do Laboratório Nacional de Engenharia Civil (LNEC). Com estes ensaios, pretendeu-se avaliar o comportamento e a capacidade das espécies ciprinícolas potamódromas (neste caso, do barbo-comum; selecionado como espécie alvo por ser representativo de outras espécies ciprinícolas potamódromas abundantes nos rios Ibéricos e da europa ocidental) de transpor pequenos açudes de faces verticais, bem como os açudes

rampeados, considerando a influência de parâmetros considerados como preponderantes na transposição destes obstáculos, tais como: a profundidade de água a jusante do açude (D), a queda a transpor (H; desnível entre a superfície livre da água a jusante e o topo da soleira do açude), e o comprimento da soleira (W), no caso dos açudes de faces verticais; o comprimento da rampa (L), e a sua inclinação (S), quando se trata dos açudes rampeados. Ainda no caso dos açudes rampeados, foi igualmente avaliada a adição de diferentes substratos ao longo da rampa, como possível medida de requalificação destas estruturas. As diferentes configurações testadas, resultantes da combinação dos referidos parâmetros, foram ainda testadas ao longo de uma variedade de caudais (Q). Os exemplares de barbo-comum utilizados nos ensaios foram capturados no rio Lisandro através de pesca elétrica. Em todos os ensaios, cada configuração testada teve 4 réplicas, usando em cada réplica um cardume de 5 peixes (n = 20 peixes por configuração). Antes do início de cada ensaio, os peixes foram mantidos durante 15 minutos na área de aclimatação, localizada na parte mais a jusante do canal, para se adaptarem às condições. Após esse período, puderam movimentar-se livremente durante um período máximo de 60 minutos. Tanto as passagens para montante como para jusante foram permitidas, portanto, os peixes puderam transpor os diferentes açudes várias vezes. Em cada ensaio foi registada a seguinte informação: número de aproximações (i.e., o número de peixes que entraram na área de aproximação); número de tentativas de passagem (i.e., o número de peixes que tentaram ativamente transpor o açude dentro da área de aproximação); número de sucessos de passagem, para montante e para jusante; o comportamento de passagem, salto vs. natação, no caso dos açudes de faces verticais; o tempo de ensaio decorrido a cada passagem. Com base nesta informação calculou-se a eficiência de atração (EA), correspondente ao quociente entre o número de tentativas e o número de aproximações registadas, e também a eficiência de passagem (EP), dada pelo quociente entre o número de passagens para montante e o número de tentativas. Os principais resultados destes ensaios laboratoriais sugerem que, no que diz respeito aos açudes de faces verticais, i) a capacidade de transposição do barbo-comum foi inibida pela ocorrência de baixas profundidades de água a jusante do açude em associação com elevadas quedas de água a transpor; ii) o comportamento de passagem dependeu da combinação de profundidade de água a jusante com a queda de água a transpor; e iii) o comprimento da soleira influenciou as passagens para jusante, mas não as transposições para montante. Quanto aos resultados dos ensaios com os açudes rampeados, i) a transposição foi condicionada pelo aumento do comprimento da rampa, e da sua inclinação; e ii) a aplicação de substratos naturais, como pedras, pode aumentar a permeabilidade das rampas à movimentação dos peixes. Estes resultados são úteis para identificar os possíveis obstáculos à migração, e para ajudar a desenvolver medidas de requalificação para projetar estruturas mais facilmente transponíveis para os peixes.

Contents

List of Figures

I. Introduction

II. Small Instream Obstacles Assessment

III. Small Broad–Crested Weirs

IV. Low–Head Ramped Weirs

List of Tables

II. Small Instream Obstacles Assessment

III. Small Broad–Crested Weirs

IV. Low–Head Ramped Weirs

I. Introduction

1. Rivers, connectivity and small instream obstacles

1.1. Rivers

Rivers have long been exploited by human populations, serving a wide variety of uses. The majority of the main cities of the world are associated to rivers that were, and still are, used as a source of freshwater for populations and industry, food (mostly fish), transport, hydropower, recreation, and as a means of disposing of rejects (Wilson and Carpenter 1999; Jackson et al. 2001; Postel and Richter 2003). Consequently, all these uses have had large-scale effects on rivers, which are being progressively impacted by water abstraction, river channelization, damming, fragmentation, and water pollution (Jackson et al. 2001; Haidvogl 2018). Among the aquatic biota, freshwater fish, which are recognized to respond significantly and often predictably to these anthropogenic disturbances (Li et al. 2010; Moog et al. 2018), are the most endangered species (Aarts et al. 2003; Nilsson et al. 2005; Reid et al. 2019).

Iberian rivers are highly influenced by Mediterranean climatic conditions, presenting a strong inter-seasonal and inter-annual variability in river flows (Ferreira et al. 2007; Hermoso and Clavero 2011; Skoulikidis et al. 2017). They are typically characterized by annual cycles of floods, due to cool rainy winters, and droughts, resulting from the extended dry summers, that usually varies in intensity according to levels and duration of annual and interannual rainfall (Gasith and Resh 1999; Branco 2013; Skoulikidis et al. 2017). Water uses and management practices in these watercourses have to deal with such natural variability (Skoulikidis et al. 2017). Freshwater species, including fish, have adapted to this seasonality, showing considerable resilience and developing rapid colonization strategies (Lucas and Baras 2001; Magalhães et al. 2007). However, over the last decades, due to the rising water demand for agricultural, industrial, and urban development, the seasonal dryness has been intensified, and with that, widespread pressures on water resources considerably increased, affecting fundamentally the natural flow regime and consequently river connectivity (Datry et al. 2014; Skoulikidis et al. 2017). Therefore, freshwater species present in this region, that is considered a global hotspot of biodiversity, endemism, and related ecosystem services, are now among the most endangered species worldwide (Myers et al. 2000; Skoulikidis et al. 2017).

1.2. River connectivity

River connectivity is considered one of the main factors influencing the distribution of species in riverine ecosystems (Fahrig and Merriam 1985; Aarts et al. 2003; Calles and Greenberg 2009). The scientific term "connectivity" started to be used in the 80s, with the River Continuum Concept postulated by Vannote et al. (1980), followed by Ward (1989), with the Extended Serial Discontinuity Concept and the four-dimensional nature of rivers (Seliger and Zeiringer 2018). It describes essentially the spatial connections within river systems (longitudinal, lateral, and vertical dimensions), encompassing also a temporal heterogeneity and the anthropogenic alterations (Vannote et al. 1980; Ward 1989; Wiens 2002; Seliger and Zeiringer 2018). As schematised in Figure 1.1, longitudinal connectivity represents the connection along the channel, from headwaters to confluences and the sea; lateral connectivity refers to the connection between the main channel and to the adjacent riparian/floodplain system; vertical connectivity represents the connection between surface and ground waters, from the river towards the hyporheic interstitial and the groundwater; and the temporal dimension that considers the existence of a hierarchy of time scales in ecological systems.

The loss of river connectivity (particularly the longitudinal dimension) by flow regulation and habitat destruction or degradation, due to river fragmentation by weirs and dams, is pointed out by several authors (e.g. Ovidio and Philippart 2002; Aarts et al. 2003; Nilsson et al. 2005; Calles and Greenberg 2009; Gozlan et al. 2019; Reid et al. 2019) as the most serious pressure to the sustainability of fish populations, having led to declines of more than 50% of the threatened fish species in Europe (Northcote, 1998). Actually, in studies of fish populations integrity and dynamics (e.g. characterization of populations and communities, studies on diversity (α, β, γ), migratory movements assessments), the longitudinal connectivity is probably the most well-known dimension, mainly due to its extensive influence on upstream and downstream migrations that fish undergo between different habitats, such as feeding, spawning and refuge habitats (Lucas and Baras 2001; Calles and Greenberg 2009; Branco et al. 2014; Reid et al. 2019). For this reason, fish are considered good indicators of connectivity conditions in watercourses (Jungwirth et al. 2000; Seliger and Zeiringer 2018).

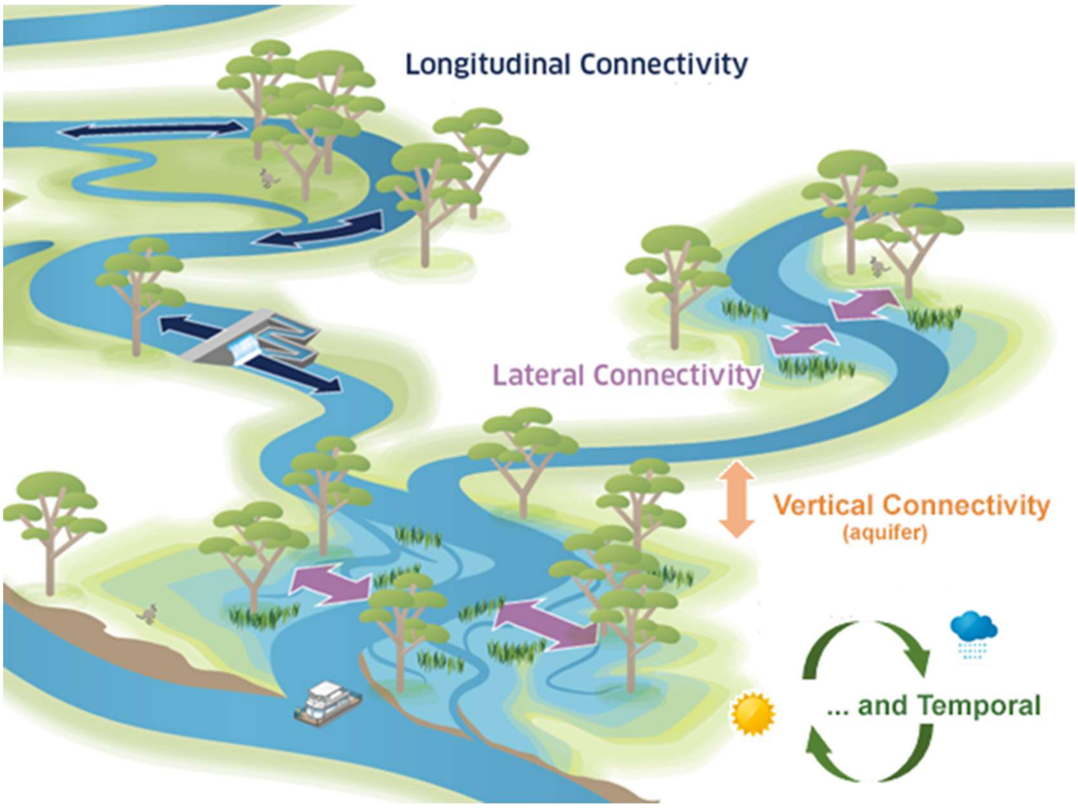

Fig. 1.1. Representation of the four-dimensional nature of rivers. River connectivity acts on one temporal dimensional and three spatial connections: longitudinal (along the river), lateral (connecting the river channel to the floodplain), and vertical (between surface and ground waters) (adapted from https://www.mdba.gov.au/managing-water/water-for-environment/river-flows-connectivity).

1.3. Small instream obstacles

Habitat degradation due to river fragmentation by hydraulic infrastructures, along with flow regulation, are indicated as main causes responsible for about 48% of flow regime alterations (Grill et al., 2015; Reid et al. 2019). Over the last decades, the number of large dams and especially small hydropower plants has greatly increased, due to promotion of renewable energies and growing water supply demands for agriculture, industry and cities (Crook et al. 2015; Kelly-Richards et al. 2017; Couto and Olden 2018). Mostly after the 1970s, numerous studies have been made on impacts of large man-made barriers on riverine ecosystems (Nilsson et al. 2005; Santos et al., 2006; Silva et al. 2017) in order to find solutions to overcome or minimize their adverse effects particularly for fish fauna, such as the implementation of fish passage devices (Larinier and Marmulla 2004; Katopodis and Williams 2012; Birnie-Gauvin et al. 2019). Nevertheless, not only dams are barriers to fish migration. The presence of other artificial obstacles, such as small weirs (Figure 1.2), can be a partial or a full barrier for many fish during their upstream migration (Lucas and Baras 2001; O'Hanley 2011; Birnie-Gauvin et al. 2019). However, the impacts on the river system of small weirs have received much less attention (Ovidio and Philippart 2002; Poulet 2007; Ordeix et al. 2011; Newton et al. 2018), because they are considered as "small barriers" and "a priori permeable" to fish movements.

Fig. 1.2. Image of a small weir located in the Alviela river, Portugal. (photo courtesy of J.M. Santos)

Worldwide, small weirs are far more numerous than dams (Nilsson et al. 2005; Ordeix et al. 2011; King et al. 2017). Only in Portuguese rivers there are more than 8000 small weirs (Ordeix et al. 2018). As for the rest of the European countries, these weirs were mostly constructed between the 10th and 19th centuries with the main function of water storage and supply, especially for irrigation, but some were also adapted into small hydropower plants (Santos et al. 2006; Birnie-Gauvin et al. 2017). According to Solà et al. (2011), these obstacles, that are in general less than 5 m in height (ONEMA 2010; Solà et al. 2011; Baudoin et al. 2014), can be classified considering the design into three main types (Figure 3): small broad-crested weirs, low-head ramped weirs, and culverts. In Portuguese rivers, the small broad-crested weirs (Figure 3A), which have a vertical downstream face, and the low-head ramped weirs (Figure 3B), with inclined faces that fish may be able to negotiate by swimming and that do not generate a waterfall, are the two designs most present.

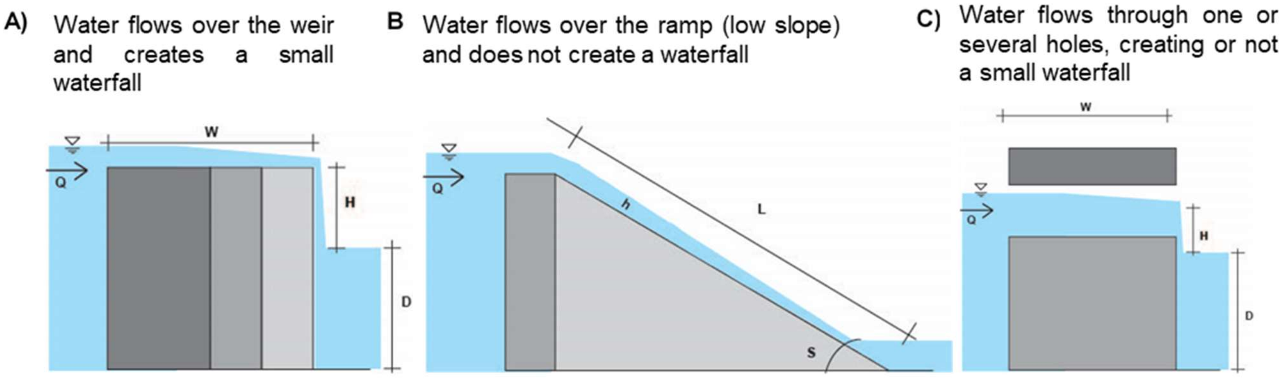

Fig. 1.3. Illustration of main types of small man-made instream obstacles, according to Solà et al. 2011: A) broad-crested weir; B) low-head ramped weir; C) culvert. For each obstacle, the factors that may influence the successful negotiation by fish are also presented: width of the obstacle (W); waterfall height to overcome (H); plunge pool depth downstream (D); ramp length (L); ramp slope (S); water column over the ramp (h); and discharge (Q) (adapted from Solà et al. 2011).

The permeability of small weirs to fish movements, both of small broad-crested and low-head ramped weirs, should be considered as site-, season-, and species-specific (Baudoin et al. 2014; Kelly-Richards et al. 2017). Therefore, the effect that these instream obstacles have on fish migratory movements may not be linearly related to the number of small weirs that fish need to negotiate, but closely dependent on the physical characteristics of the weirs, on the hydrodynamic conditions present in the vicinity of the structure, and on involved fish swimming abilities (Solà et al. 2011; Baudoin et al. 2014; Harris et al. 2016), which are directly associated to fish species guilds and body size (Kemp and O'Hanley 2010; Katopodis and Gervais 2016; Newton et al. 2018). Therefore, as advocated by some authors, the assessment of fish passage performance over these obstacles should contemplate the study of those key physical and hydraulic parameters, such as (Figure 3): plunge pool depth (D), waterfall height (H) and the weir crest width (W), for broad-crested weirs (Powers and Orsborn 1985; Kondratieff and Myrick 2006; Ovidio et al. 2007; Ficke et al. 2011; Baudoin et al. 2014); the ramp length (L) and slope (S), for low-head ramped weirs, (Baudoin et al. 2014; Baker 2014; Landsman et al. 2018; Plesiński et al. 2018); and, as a general parameter, the discharge (Q), and consequently water velocity and turbulence (Kemp et al. 2011; Baudoin et al. 2014; Harris et al. 2016).

Presently, many small weirs have ceased to perform the function for which they were implemented, thus becoming obsolete or non-operational. According to the European Water Framework Directive guidelines (WFD; European Commission 2000), that recognize the need of re-establish free movements for all fish species and size-classes to guarantee a good ecological quality in rivers, member states should assess all instream obstacles, including small weirs, and minimize their barrier effect (Reyjo et al. 2014; Barry et al. 2018). Some of these weirs that, after being assessed, cannot be removed due to its social, economic, and/or historical significance, have undergone maintenance and rehabilitation works to enhance fish passability, such as those executed in the requalification project 'Habitat restoration for diadromous fish in river Mondego, central Portugal' (http://www.rhpdm.uevora.pt/index.html). In this project, two main retrofitting measures were implemented in five old weirs, in order to afford a more holistic negotiation by fish (FAO/DVWK 2002; Baker 2014; Baudoin et al. 2014): the inclusion of nature-like fish ramps in the weirs design, and the addition of natural substrates to the ramps, that may mimic natural stream conditions and promote energy dissipation (Figure 4).

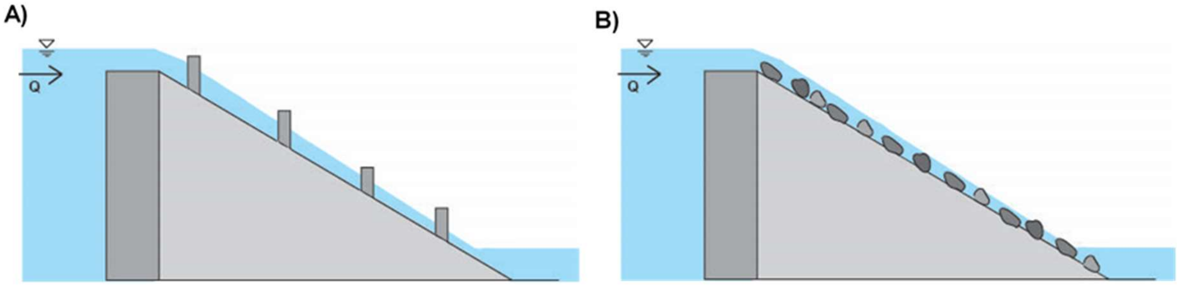

Fig. 1.4. Illustration of some retrofitting solutions possible to implement on ramped weirs considering the addition of different types of substrates to the ramp: A) use of boulders; B) use of natural substrate like cobbles.

The addition of natural substrates, like pebbles, cobbles or boulders, to instream obstacles and fish transposition devices has been successfully implemented since the early 1970s (Katopodis and Aadland 2006). In low-head ramped weirs, this retrofitting solution is frequently used to increase bed roughness, and consequently promote energy dissipation, creating localized zones of low-velocity and turbulence (Towler et al. 2015; Muraoka et al. 2017; Rodgers et al. 2017; Plesiński et al. 2018) that may be used by fish as resting areas during the upstream negotiation of ramps (Liao 2007; Elder and Coombs 2015; Landsman et al. 2018; Knapp et al. 2019). These low velocities, created by the imbedded roughness elements, may be especially important to species of weaker swimming capabilities (Santos et al. 2014; Baudoin et al. 2014; Benitez et al. 2015). The substrate dimensions and the spatial arrangement are considered important factors for the establishment of suitable hydrodynamic conditions that may facilitate the successful negotiation by fish (Muraoka et al. 2017; Johnson et al. 2019; Knapp et al. 2019). However, the effectiveness and efficiency of most retrofitting solutions continues poorly understood, and therefore, more studies are needed.

2. Fish and migratory movements

Freshwater fish represent about 40% of all known fish species, and are probably the most studied fauna in freshwater ecosystems (Gozlan et al. 2019; Reid et al. 2019). Worldwide, for thousands of years, human populations have depended on freshwater fish as a food resource, being diadromous species (e.g. salmonids, eel, lamprey) the most valued (Lucas and Baras 2001; Brink et al. 2018; FAO 2018). However, as mentioned before, the sustainability of fish populations is increasingly at risk due to direct impacts of human activities (e.g. building of hydraulic infrastructures, flow alterations from hydropower, water extraction; water pollution and habitat degradation) and global change environment, such as the frequency increase of droughts and floods (Reyjo et al. 2014; Brink et al. 2018; Reid et al. 2019).

In Iberian rivers, 80% of the continental autochthonous fish species are endemic, resulting from a large speciation process (Doadrio et al. 2011; Romão 2018). The family Cyprinidae is the most represented, being present in all Iberian watercourses (Doadrio et al. 2011; Santos et al. 2011; Benitez et al. 2015). As the majority of other species, cyprinid fish adapted their life patterns in response to habitat distribution and availability, attending mostly to longitudinal connectivity over space and time (Ward 1989; Lucas and Baras 2001; Baudoin et al. 2014). In that way, to optimize the use of resources, cyprinids species performe targeted “habitat shifts” (Seliger and Zeiringer 2018), exploring various habitats (Figure 2.1) with specific characteristics, attending to life-stage requirements (e.g. growth, reproduction, shelter and protection from predators) or habitat alterations (e.g. due to floods) (Northcote 1998; Wiens 2002; Seliger and Zeiringer 2018). Unlike diadromous salmonids, which inhabit both sea and freshwater habitats during certain life stages, cyprinid species are mostly potamodromous that only migrate in freshwater systems (Lucas and Baras 2001; Thurow 2016). These migratory movements, which can range from a few meters to tens of kilometres, are mainly related to seasonal movements for spawning and habitat shifts for refuge (e.g. winter habitats, flood migrations), and, more routinely, for feeding/nutrition (Lucas and Baras 2001; Baudoin et al. 2014; Thurow 2016; Seliger and Zeiringer 2018).

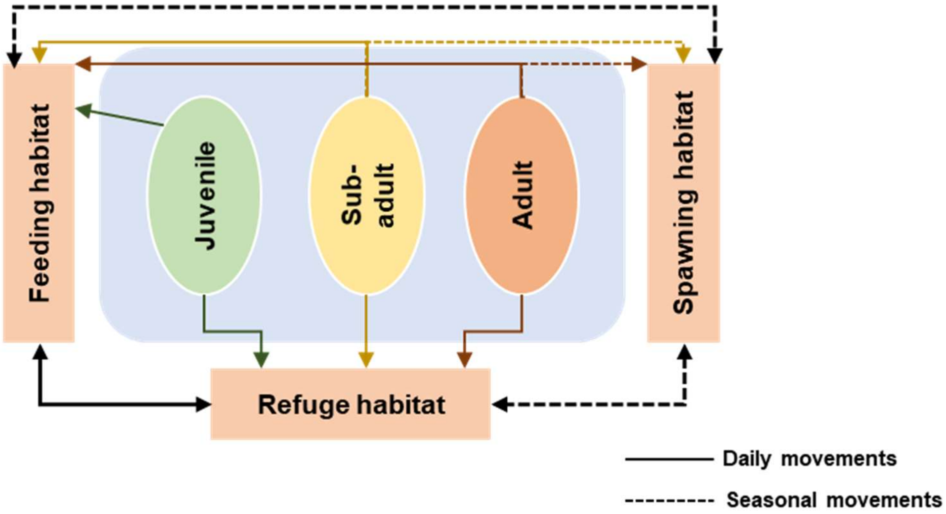

Fig. 2.1. Representation of potamodromous migratory movements between different intra-river functional habitats: refuge, feeding and spawning. (adapted from Lucas and Baras 2001, and Baudoin et al. 2014).

As mentioned by Benitez et al. (2015), particularly for salmonids, the upstream migration of mature fish to spawn has been widely studied due to its importance for species conservation. However, for potamodromous cyprinids, there are fewer studies and, therefore, the frequency, range and the intensity of upstream/downsteam movements for these species are still less understood (Lucas and Baras 2001; Ovidio and Philippart 2002; Baudoin et al. 2014; Thurow 2016), especially when facing small instream barriers (Solà et al. 2011; Baudoin et al. 2014) (assumption on which this thesis is based). Nevertheless, it is known that, among potamodromous cyprinids, upstream/downstream movements are part of common process within the population (Northcote 1998; Baudoin et al. 2014; Thurow 2016), which may be generally stimulated by interacting factors such as water temperature, season, light, discharge, water quality, as well as internal factors like the phisiological condition of fish or the homing effect (Pavlov 1989; Lucas and Baras 2001; Baudoin et al. 2014). Therefore, the mobility patterns of these species is considered very characteristic, with the main migratory movements to spawn occurring mostly during spring and early summer (Lucas and Baras 2001; Santos et al. 2005; Baudoin et al. 2014).

The swimming ability of fish depends upon their intrinsic aptitude, considering the conciliation between locomotor capacity and energy consumption (e.g. the speed at which it can swim and the duration that its speed can be maintained), with the stabilization and orientation capability (Lucas and Baras 2001; Liao 2007; Thurow 2016). This ability can vary greatly between species, particularly due to, as mentioned before, species guilds and fish body size (Kemp and O'Hanley 2010; Katopodis and Gervais 2016; Newton et al. 2018), but is also intrinsically related to habitat conditions, such as water temperature, habitat diversity, presence of instream obstacles, hydrodynamic conditions like discharge, water velocity and turbulence, etc. (Lucas and Baras 2001; Ovidio et al. 2007; Baudoin et al. 2014; Thurow 2016).

Potamodromous cyprinid species (e.g. Iberian barbel *Luciobarbus bocagei*, Steindachner 1864) may be particularly affected by the presence of small weirs along watercourses, especially by small broad-crested weirs and low-head ramped weirs. According to Solà et al. (2011), potamodromous cyprinids are considered species with a moderate or low capacity to overcome these barriers, due to their limited swimming and jumping abilities when compared to adult salmonids (Baudoin et al. 2014; Katopodis and Gervais 2016; Ovidio and Philippart 2002; Silva et al. 2009). In fact, these species are referenced by some authors as "non-jumping species" (Doadrio 2011; Baudoin et al. 2014) due to their demonstrated reduced propensity in negotiating obstacles by jumping. Baudoin et al. (2014), refers several studies that mention the presence of potamodromous cyprinids retained at the foot of small weirs, because they had little motivation or were unable to jump to overcome the obstacle, indicating that the most usual passage behaviour of potamodromous cyprinids to negotiate small weirs is by swimming through the water nappe formed in the downstream face of the structure (Baudoin et al. 2014).

Along with the physical constraint that small weirs inflict on fish movements, the presence of these instream structures significantly alter hydrodynamics conditions, which in turn influence the swimming ability of potamodromous cyprinids. Discharge, and consequently water velocity and turbulence, can trigger or inhibit the migratory movements of fish (Lucas and Baras 2011; Baudoin et al. 2014; Thurow

2016), depending on the magnitude and the way they are perceived by individuals (Liao 2007; Tritico and Cotel 2010; Lacey et al. 2012). As mentioned by Liao et al. (2007), if flow has a predictable spatial-temporal characteristic (Figure 2.2A), meaning that the vortices (or eddies) created due to velocity gradients are similar in intensity and size, which provides sufficient stability to individuals, fish may be attracted to turbulent flows. On the other hand, if flow field presents wide spatial variations and high turbulence intensities (Figure 2.2B), and consequently strong eddies, that may interfere with stability and swimming trajectories, fish tend to become disoriented and may reduce the swimming performance. Therefore, the eddies diameter, vorticity and orientation relative to the fish trajectories are referred as important factors on fish stability and swimming performance (e.g. fish tend to became disoriented upon eddy diameters larger than 50–75% of the fish body total length) (Pavlov et al., 2000; Liao, 2007; Tritico and Cotel 2010; Silva et al. 2012), thus, influencing the ability of fish to approach, attempt, and successfully negotiate these small weirs, both broad-crested weirs and low-head ramped weirs.

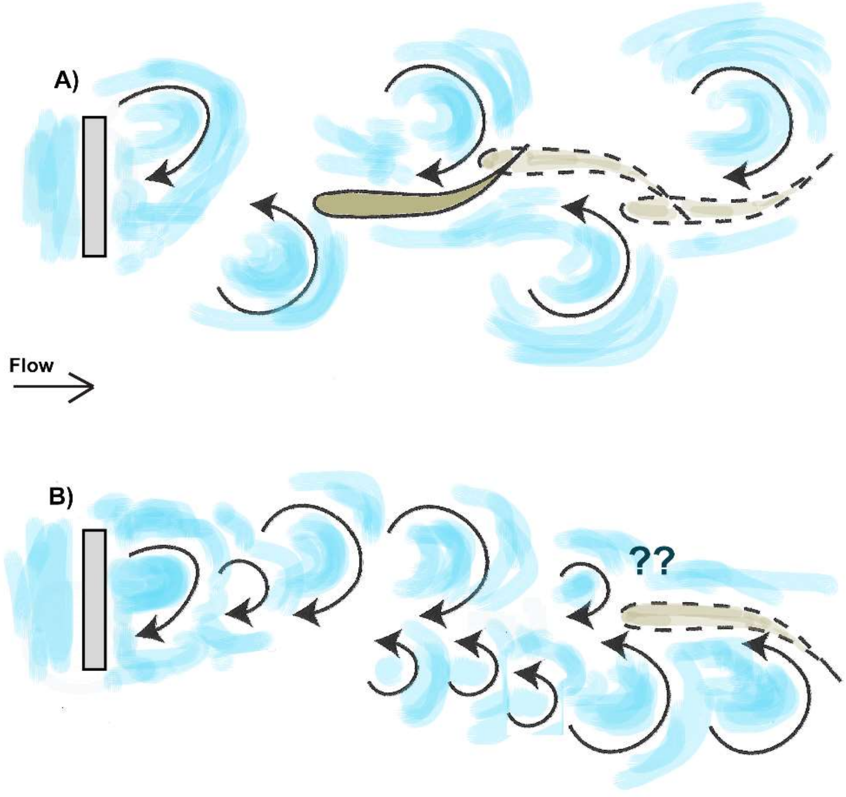

Fig. 2.2. Illustration of the influence of turbulence (eddies) on fish behaviour (orientation and swimming ability), considering: A) occurrence of predictable spatiotemporal turbulence (periodic eddies); B) occurrence of unpredictable turbulence (non-periodic eddies) (adapted from Liao et al. 2007, and Lacey et al. 2012).

3. Objectives and thesis structure

3.1. Objectives

As mentioned before, considering there are only a few studies about the influence of small instream man-made barriers (e.g. small weirs, culverts) on migratory movements of fish, which are mainly focused on salmonid species, this thesis aimed to attained a comprehensive understanding on how Iberian potamodromous cyprinids deal with these small obstacles, in particular with small broad-crested weirs and low-head ramped weirs. Therefore, the two main goals of this study were:

I. increase the knowledge on fish behaviour, especially on Iberian potamodromous cyprinids, for dealing with problems of existing small instream obstacles, like small weirs;
II. study different designs to improve the permeability of these small barriers for Iberian potamodromous cyprinid species.

Three major interconnected tasks of fish-hydraulic experiments, based on fish response to hydraulic characteristics of small broad-crested weirs and low-head ramped weirs, were performed in the field and in a laboratory facility, in order to achieve the main goals mentioned above, and respond to the following detailed objectives:

1. catalogue and assess the influence of the most common types of small instream obstacles in a non-impacted (physical disturbance aside) upstream segment of a mid-sized stream on migratory movements of Iberian barbel (*Luciobarbus bocagei*);
2. evaluate the passage performance (e.g. swimming ability, passage behaviour, attraction and passage efficiencies) of Iberian barbel (*Luciobarbus bocagei*) negotiating a small experimental broad-crested weir adjustable for different plunge pool depths (D), waterfall heights (H), and weir crest widths (W), under different discharges (Q);
3. test the passage performance of Iberian barbel (*Luciobarbus bocagei*) negotiating an experimental low-head ramped weir with varying ramp length (L) and slope (S), considering also the effect of distinct retrofitting solutions (addition in the ramp of different types of substrates, with different arrangements), under different discharges (Q).

In all the experiments performed, Iberian barbel was selected as the target species due to its consistent abundance in Iberian rivers and for being considered as a representative of at least seven other species of medium-sized benthic potamodromous cyprinids (encompassing species from the genera *Barbus* and *Luciobarbus*) commonly present in Iberian and Western European rivers (Santos et al. 2014; Romão et al. 2018).

3.2. Thesis structure

This thesis is arranged into five main parts that are presented below. With the exception of parts I and V, which correspond respectively to the Introduction and the General discussion of the thesis, the parts II, III and IV present the field (II) and experimental (III and IV) studies performed to accomplish the detailed objectives previously established. Each study corresponds to a stand-alone scientific paper that has been published in a peer-reviewed journal. The manuscripts contents were kept identical to the published versions, presenting only minor changes in the formatting, to standardize the thesis presentation.

Thus, this thesis has the following parts:

I. Introduction – In this initial part, a literature review is presented, to provide the reader with the state of the art on the main topics addressed in this study. The main goals and specific objectives are also defined, as well as the structure and organization of the thesis.

II. Small instream obstacles assessment – This part consists of one main chapter that presents the field study performed in the 5.6 km upstream segment of the Alviela River, a stream only impacted by physical barriers, to understand how small weirs affect the movements of Iberian barbel in the wild. Small weirs present in the study segment were identified and seasonally characterized, and Iberian barbel were marked with Visible Implant Elastomer tags (VIE), and seasonally sampled, to assess possible fish displacements between barriers.

III. Small broad-crested weirs – This part encompasses the laboratory experiments performed in an indoor ecohydraulic flume using an experimental small broad-crested weir. It consists of three different papers, corresponding to three chapters, that are mainly focused on:

1. the influence of key parameters, such as different combinations of plunge pool depths (D) and waterfall heights (H), under different discharges (Q), on the upstream passage performance of Iberian barbel;
2. the effect of different plunge pool depths (D), waterfall heights (H), and weir discharges (Q) on the passage behaviour (swimming vs. jumping) of Iberian barbel;
3. the influence of different weir crest widths (W) and discharges (Q) on upstream and downstream passage performance of Iberian barbel.

IV. Low-head ramped weirs – This part is divided in two chapters, corresponding to two laboratory studies that were performed in the same flume, using different experimental low-head ramped weirs. These two studies were essentially focused on:

1. the effect of different combinations of ramp length (L) and slope (S) on the upstream passage performance of Iberian barbel;
2. the influence of different retrofitting designs (RD), tested under two discharges (Q), on the upstream passage of Iberian barbel.

V. General discussion and conclusions – In this final part, a general discussion and the main conclusions of this thesis are presented, considering all the experimental studies performed; some future research guidelines are summarized as well.

3.3. List of publications

A list of the scientific papers, published in peer-reviewed journals, that are part of this thesis is presented below.

II. Small instream obstacles assessment

1. Branco, P.; Amaral, S.D.; Ferreira, M.T., Santos, J.M. 2017. Do small barriers affect the movement of freshwater fish by increasing residency? Science of The Total Environment, 581-582: 486-494. http://dx.doi.org/10.1016/j.scitotenv.2016.12.156.

III. Small broad-crested weirs

1. Amaral, S.D.; Branco, P.; Silva, A.T.; Katopodis, C.; Viseu, T.; Ferreira, M.T.; Pinheiro, A.N.; Santos, J.M. 2016. Upstream passage of potamodromous cyprinids over small weirs: the influence of key-hydraulic parameters. Journal of Ecohydraulics, 1: 79–89. http://dx.doi.org/10.1080/24705357.2016.1237265. (Best student paper 2016 in the Journal of Ecohydraulics).
2. Amaral, S.D.; Branco, P.; Katopodis, C.; Ferreira, M.T.; Pinheiro, A.N.; Santos, J.M. 2018. To swim or to jump? Passage behaviour of a potamodromous cyprinid over an experimental broad-crested weir. River Research and Applications, 34: 174–182. https://doi.org/10.1002/rra.3232.
3. Amaral, S.D.; Branco, P.; Romão, F.; Viseu, T.; Ferreira, M.T.; Pinheiro, A.N.; Santos, J.M. 2018. The effect of weir crest width and discharge on passage performance of a potamodromous cyprinid. Marine and Freshwater Research, 69. 1795–1804. Special Issue: Fish Passage 2018 & Hydropower Symposium. https://doi.org/10.1071/MF18075.

IV. Low-head ramped weirs

1. Amaral, S.D.; Branco, P.; Katopodis, C.; Ferreira, M.T.; Pinheiro, A.N.; Santos, J.M. 2019. Passage Performance of Potamodromous Cyprinids over an Experimental Low-Head Ramped Weir: The Effect of Ramp Length and Slope. Sustainability, 11. 1456. https://doi.org/10.3390/su11051456.
2. Amaral, S.D.; Quaresma, A.L., Branco, P.; Romão, F., Katopodis, C.; Ferreira, M.T.; Pinheiro, A.N.; Santos, J.M. 2019. Assessment of retrofitted ramped weirs to improve passage of potamodromous fish. Water, 11. 2441. https://doi.org/10.3390/w11122441.

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II. Small Instream Obstacles Assessment

1. Do small barriers affect the movement of freshwater fish by increasing residency?

Branco, P.; Amaral, S.D.; Ferreira, M.T., Santos, J.M. 2017. Do small barriers affect the movement of freshwater fish by increasing residency? Science of The Total Environment, 581-582: 486-494. http://dx.doi.org/10.1016/j.scitotenv.2016.12.156

1.1. Abstract

River fragmentation due to artificial barriers directly impacts fish communities by limiting migratory movements. This work aims to understand how small barriers affect the movements of a potamodromous cyprinid species – the Iberian barbel (*Luciobarbus bocagei* (Steindachner, 1864)) – in a 5.6 km upstream segment of a stream impacted only by the presence of physical barriers. Fish were marked with Visible Implant Elastomer tags (VIE), and barriers were seasonally characterized. A total of 683 fish were tagged, with 104 recaptures, during five sampling seasons (spring 2012 – early summer 2013). Eleven of the recaptured fish moved past a barrier, without any preference in terms of direction of movement. There were no differences in length, either between migrants and residents, or between upstream and downstream migrants. The results show that although barbel are able to negotiate small barriers, part of the population did not move between fragmented reaches – an indication that under such conditions, fish species populations may adjust their life-history strategy to augment residency as it was hypothesized from the results.

1.2. Introduction

Freshwater fish is one of the most threatened biological groups and is expected to be among the most severely impacted by climate change, due to a wide range of present and future anthropogenic stressors with an impact on rivers (Ficke et al. 2007; Comte et al. 2013; Beatty et al. 2014). Freshwater fish from Southern-European regions are particularly imperiled, as increased flow reduction due to water extraction and climate change in this geographic area are major threats (Hermoso and Clavero 2011; Maceda-Veiga 2013) that drastically magnify fragmentation of river connectivity.

Longitudinal connectivity is seen as the most important connectivity dimension for freshwater fish species, because it allows upstream and downstream fish migration cycles to occur (Lucas et al. 2001), and because it is vulnerable to even a single barrier that immediately isolates contiguous river segments (Jager et al. 2001). Although connectivity losses are frequently perceived as primary causes of freshwater fish species decline, with strong evidence for some fish, including diadromous species (Kocovsky et al. 2009; Liermann et al. 2012) when and how they affect the distribution of potamodromous fish it is far less clear. This is partly because local habitat conditions can mitigate connectivity losses by providing spawning grounds, food and/or environmental refugia (Magoulick

2000), and partly because fish populations are also affected by other human pressures that frequently mask or interfere with connectivity effects (Branco et al. 2012). Potamodromous species are obligatory migrants that only perform migrations within the freshwater environment, and are therefore able to use adequate habitats found between barriers. Even though this could be seen as granting these species some resilience when suitable spawning habitats are present, the impacts of barriers on potamodromous fish are nevertheless widespread (Moyle 1995; Muhar 1996; Dunham et al. 1997; Fagan et al. 2002; Morita and Yamamoto 2002). Even though potamodromy reflects an obligation to migrate, it is known that some populations include both migrants and resident fish (Chapman et al. 2011). This has spurred increased interest in the partial migration of cyprinids (Jepsen and Berg 2002; Brodersen et al. 2008; Skov et al. 2010; Chapman et al. 2011; Skov et al. 2011), which are the best known potamodromous partial migrants (Chapman et al. 2012a). Having said this, there is still a knowledge gap compared to salmonids (Jonsson and Jonsson 1993; Hendry et al. 2004) and there is thus an urgent need for further studies on this subject.

The magnitude of connectivity losses and the time period they affect are closely linked to the time of construction, size and location of the barrier, the characteristics of the river system (Petts 1984; Gehrke and Harris 2001; Gehrke et al. 2002) and the habitat loss for each particular species and life-cycle stage. Connectivity losses are therefore not linearly related to the number of obstacles, but depend on characteristics such as height, slope, and depth below the barrier (Bourne et al. 2011). Most studies, when analyzing connectivity impacts on fish, look at large obstacles, such as hydroelectric power plants (Garcia de Jalon et al. 1994; Chang et al. 1999; Mérona and Albert 1999; Peňáz et al. 1999; Gehrke et al. 2002). However, changes in species richness, diversity and community composition (Pusey et al. 1995; Reyes-Gavilán et al. 1996; Gehrke et al. 2002) can also be due to the cumulative impact of small barriers, which vastly outnumber taller ones (Nunn et al. 2008; Cote et al. 2009; Lucas et al. 2009). Although many of these smaller barriers can be considered partial or intermittent, they can be full barriers for many fish during their upstream spawning migration. Another issue that must be considered is the directionality of blockage. In the case of small barriers, even though the impact of downstream blockage is important (Fullerton et al. 2010), it is potentially limited as fish may negotiate them voluntarily or through flushing events. It is thus clear that understanding the mobility of potamodromous species through small barriers is important for enhancing conservation efforts, particularly in climate change scenarios of drought or reduced flow in rivers (Magoulick and Kobza 2003; Chessman 2013).

The present study aims to understand how small barriers in an otherwise non-impacted upstream segment of a stream, affect movements of a potamodromous fish, the Iberian barbel (*Luciobarbus bocagei* (Steindachner 1864)). The Iberian barbel is a widespread potamodromous Iberian species (Magalhães 1992; Oliveira et al. 2002) occupying both lentic and lotic environments (Doadrio et al. 1991). It tends to select areas with moderate water velocities and it incurs in spring upstream migrations to spawn in sand or gravel beds with stronger flows (Rodríguez-Ruiz and Granado-Lorencio 1992). The barbel was selected as the focus of this study since it can be considered representative of at least seven other species of medium-sized benthic potamodromous cyprinids in Western Europe (encompassing species from the genera *Barbus* and *Luciobarbus*) - all share similar ecological guilds in terms of physical habitat (benthic), reproduction strategy (lithophilic), and migratory behavior (potamodromous) (Kottelat and Freyhof 2007; Doadrio et al. 2011). This kind of approach, using a representative of a group of organisms that are independent of taxonomic restrictions but use the same set of resources, has been advocated by several authors (e.g. Fauth et al. 1996, Leonard and Orth 1988, Branco et al. 2013a). The results were analyzed and interpreted in the light of both fish displacements upstream or downstream of barriers, and fish maintenance between the same barriers throughout the study period.

1.3. Materials and methods

1.3.1. Study area

When selecting a site to study fish barrier permeability in situ, certain premises must be fulfilled. For the present study we considered that: 1) the river segment had to be free of point sources of pollution and with minimal agricultural run-off; 2) it had to be predominantly impacted by physical connectivity infringements; 3) there had to be a lack of tributaries, meaning no alternative migratory pathways; and 4) it had to harbor native potamodromous fish (encompassing a broad range of fish sizes). Candidate study sites were examined in advance from a database of N500 sampling sites across Portugal (Ferreira et al., 2007), from which a 5.6 km long reach of the Alviela River (Figure 1.1; Table 1.1) was selected due its compliance with the required criteria. The stretch is a single river segment that is unaffected by acute pollution or water abstraction, and apart from the connectivity infringement, is a well-preserved segment without any major disturbance of the system.

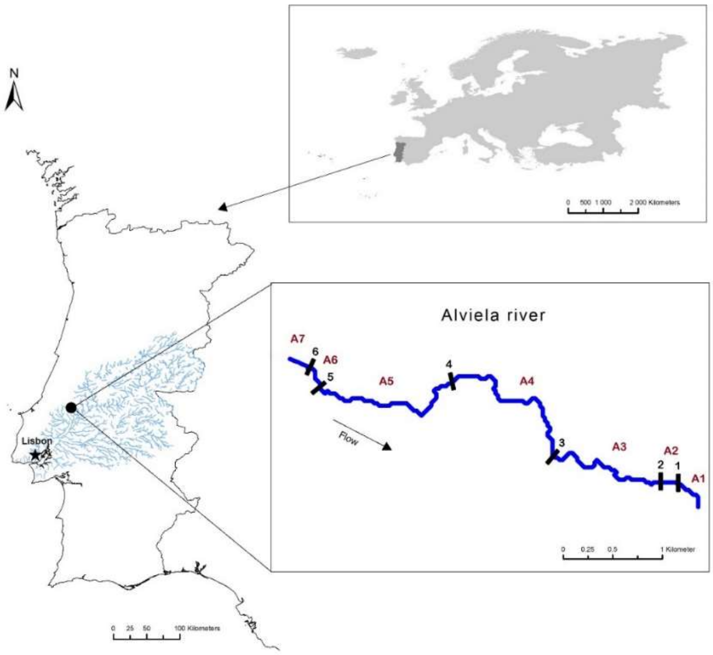

Fig. 1.1. Map and location of the study area in the Alviela River with representation of the small barriers studied (6 upstream–1 downstream) and of the areas surveyed (A7 upstream–A1 downstream).

Table 1.1. Sections of the Alviela River under study and their proportion of mesohabitats.

Section	Area (ha)	Length (m)	Proportion (%) of mesohabitats		
			riffle	run	pool
A1	0.14	160	0	80	20
A2	0.12	165	0	5	95
A3	1.27	1430	0	30	70
A4	1.33	1812	10	40	10
A5	1.04	1790	5	75	20
A6	0.30	258	15	70	15
A7	0.11	58	0	0	100
Total	4.31	5673			

1.3.2. Characterization of obstacles

The river segment was initially surveyed on foot along the banks with the goal of mapping any potential obstacle to fish movement within the river corridor and mesohabitats (pools, riffles and runs) (Table 1.1). Each structure that could block the upstream movement of fish was therefore considered an obstacle (Table 1.2). Each of these structures (n = 6) was then hydraulically characterized in the field, in terms of slope, top width of the obstacle, height of the jump, depth below the obstacle (all these variables assessed with a graduated meter rules, and a level for slope), and water velocity (measured with a flow probe, model FP101, Global Water Instrumentation, Inc., Gold River, CA, USA). Three values were measured for each variable along the obstacle and the mean was used.

In order to define the impacts of the transversal obstacles on the movements of fish species, the ICF – Index of River Connectivity (from the original *Index de Connectivitat Fluvial*) (Solà et al. 2011) was then calculated for each obstacle. ICF evaluates a barrier's impact on fish movements by measuring its degree of connectivity (derived from the present hydrological characteristics), which it does by comparing the obstacle's characteristics and the swimming and jumping abilities of the species present in a given river segment. The ICF has five levels of connectivity, ranging from very good to bad, according to the barrier's permeability to fish movements (Table 1.3). Because the impact of these barriers is linked to hydraulic parameters and the capabilities of fish that are potentially present, this ICF evaluation was performed for cyprinids – the predominant group of fish at the studied stream – at each barrier and in every sampling episode (seasonally), encompassing an annual cycle. This made it possible to determine a seasonal variation in each weir's impact on fish movements.

Table 1.2. General physical characteristics (length, width and height in meters) of the 6 barriers studied with related photographs on side. For barrier localization in the river segment please see Fig.1.1.

Barrier #	Physical characteristics			Photography
	Length	Width	Height	
1	10.4	1.7	0.95	
2	53	3.3	1.25	
3	47.3	4.5	2.25	
4	20.3	3.3	1.55	
5	14.5	0.15	1.11	
6	15.3	2.5	1.4	

Table 1.3. Characteristics of the 6 obstacles evaluated in the Alviela River. For each obstacle type (LSW - low slope weir; W- weir), the key hydraulic variables (v – water velocity(cm/s); h - height of the jump (cm); turb – presence of strong turbulence) for the ICF are shown on a seasonal basis (Solà et al. 2011). ICF score classes: I – Bad (< 25) no species or only some in particular hydrological situations can pass; II – Poor (25–49) only one or few of the fish species present can pass; III – Moderate (50–74) the majority or some of the fish groups present can pass; IV – Good (75–94) the majority of the fish groups present can pass; V – Very good all fish groups present can pass (≥ 95).

Obstacle	**A1**			**A2**			**A3**			**A4**			**A5**			**A6**		
Obstacle type	**LSW**			**LSW**			**LSW**			**LSW**			**W**			**LSW**		
Slope (%)	35.6			33.4			27.0			29.0			-			19.8		
	v	*turb*	ICF	*v*	*turb*	ICF	*v*	*turb*	ICF	*v*	*turb*	ICF	*h*	*z*	ICF	*v*	*turb*	ICF
Spring 12	2.23	yes	II	0.42	no	II	0.67	No	I	-	no	I	61	50	I	1.01	no	III
Summer	0.45	no	I	0.11	no	I	-	No	I	-	no	I	83	28	I	0.58	no	III
Autumn	2.51	yes	II	0.90	no	II	1.44	Yes	II	0.72	no	II	50	61	II	1.82	yes	III
Winter	2.94	yes	II	1.27	yes	II	1.25	Yes	III	2.54	no	III	25	86	III	2.24	yes	III
Summer13	1.45	no	I	0.74	no	II	-	No	I	-	no	I	46	65	I	0.47	no	IV

1.3.3. Fish capture and tagging

In order to maintain the welfare of the individuals, animal sampling was conducted in accordance with national and international guidelines (CEN 2003; INAG 2008). A seven-point sampling grid was selected in order to encompass one site downstream of each barrier and a site above the most upstream obstacle (Fig. 1), with one sampling point per river section (Table 1.1). Each of the sites was fish-sampled by electrofishing according to CEN (2003) standards, progressing upstream in a zigzag pattern covering all present habitats and capturing fish with dip nets. Captured fish were then placed in a mesh container located away from the influence of the electric field and fixed to the riverbed in order to keep fish in a natural environment with flowing aerated water. After the capture procedure was completed, fish were

measured for total length to the nearest mm and marked with fluorescent VIE tags (NMT - Northwest Marine Technologies Inc.). These tags are composed of a polymer which is inert and coloured, allowing simple tag identification when injected subcutaneously under a translucent tissue. Tagging was carried out in accordance with the “protection of animal use for experimental and scientific work” recommendations issued by the Directorate of Animal Protection (Direcção de Serviços de Protecção Animal). The tagging procedure followed the NMT guidelines for VIE tags (Northwest Marine Technology, 2008). For consistency, fish were always tagged by the same operator. A fish-tagging code was developed to allow site and season identification by combining two VIE tags with three different fluorescent colours (red, orange and yellow – using the NMT VIE colour code generator (Northwest Marine Technology 2008)) and four body locations (Figure 1.2).

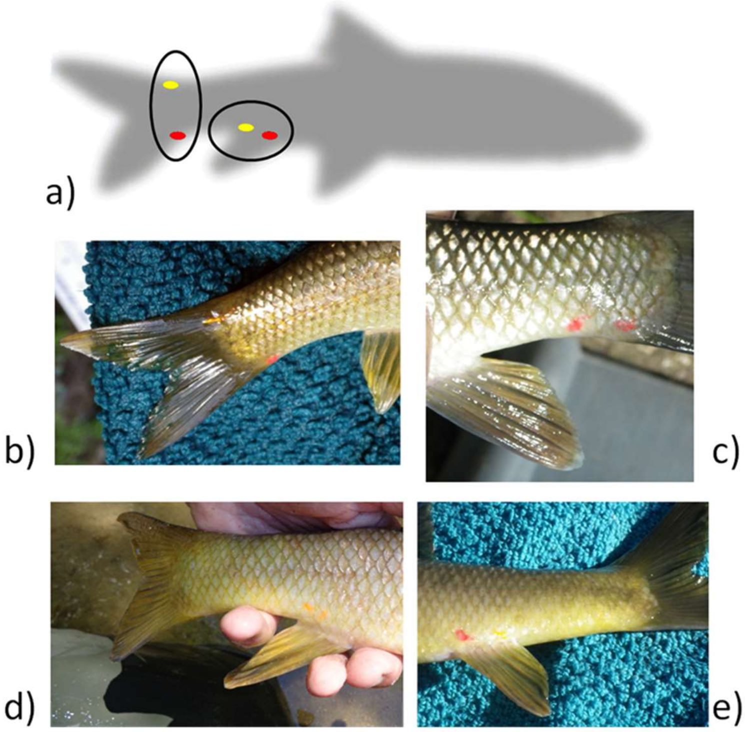

Fig. 1.2. a) Schematic view of a fish with two of VIE-tagging loci used in the study, these two loci were also mirrored on the left side of the fish to allow four tagging location to discriminate among the four tagging episodes; b) right side caudal peduncle tag; c) left side caudal peduncle tag; d) right side base of anal fin tag; e) left side base of anal fin tag.

Fish were marked during four seasonal marking episodes, each corresponding to a different season and hydrological condition: spring 2012 (two marks on the right side of the caudal fin), summer 2012 (two marks on the left of the caudal fin), autumn 2012 (two marks on the left of the anal fin), and winter 2013 (two marks on the right of the anal fin). To complete the sampling year there was an additional fifth sampling episode during the early summer of 2013, solely for sampling. In each capture campaign, fish were all monitored for tags by using an ultra-violet (UV) light to augment fluorescent tag detection. Every effort was made to minimize stress and no fish were sacrificed to complete this study; all fish were returned alive to the river at the end of each sampling.

1.3.4. Data treatment

A Mann-Whitney test was applied in order to understand whether fish size varied significantly between marked and recaptured individuals. To test if there were differences in the number of fish that moved past a barrier and the number of fish that remained between two barriers, a Chi-square-based test for the comparison of two proportions was applied. A Mann-Whitney test was performed to test for differences in size between movers (fish that moved past a barrier in either an up or a downstream direction) and stayers (fish that remained between the same two barriers). Finally, a Chi-square proportions test was used to determine whether there were preferences in terms of direction of movement (i.e. if there was a larger proportion of fish moving upstream than downstream). The Chi-square proportions tests were performed in MedCalc software (MedCalc Software bvba), and the Mann-Whitney tests were performed in STATISTICA software (STATSOFT 2000).

1.4. Results

1.4.1. Index of river connectivity (ICF)

All but one obstacle recorded at the river segment were low-slope weirs (LSW) – i.e. structures where water passes over the surface, but does not generate a small waterfall (sensu (Solà et al. 2011)). Only one obstacle (#5) was classified as a typical weir – i.e. where water passes over a structure by creating a small waterfall. ICF values (Table 1.3) proved unfavourable to longitudinal connectivity, ranging from “Bad” to “Moderate”, with a single score of “Good” achieved at weir #6 during the last sampling episode (early summer 2013). The more favourable scores (moderate) were attained in winter. All the evaluated

barriers were insurmountable (ICF - Bad) in summer, and most of them in spring as well. There was also an observable increase in barrier permeability to fish movements with the increase in water availability following the natural hydrological cycle (Table 1.3).

1.4.2. Fish

A total of 683 fish were tagged during the four marking episodes (Table 1.4). Of these, 104 individuals were recaptured, for an overall recapture rate of 15.2%. Although eleven (10.6%) of the recaptured fish moved past barriers, the majority of barbel remained between the same barriers (89.4%; X^2 = 126.173, p < 0.0001), and the ones that moved past a barrier did so without any preference in terms of direction of movement (upstream vs. downstream - $X^2 = 1.81\times10^{-17}$, p = 1). Overall, there were no differences in length, either between fish that moved (25.5 ± 5.2 cm) and fish that remained between the same barriers (25.7 ± 8.4 cm) (U = 494.5, p = 0.857), although some movement activity (12.5%) was detected for small adult barbel (150–350 mm (Oliveira et al., 2002)) (Table 1.4). Differences between upstream and downstream movers were also not detected (U = 12.0, p = 0.584). Looking at the distance travelled by the movers (Table1. 5), we can see that the fish which moved the furthest did so while progressing upstream (0–5000 m), whereas downstream movements were always shorter (< 2000 m).

Table 1.4. Recapture data of Iberian barbel (*Luciobarbus bocagei*) analyzed according to size and residency.

Size class	**N of**	**N of recaptured fish**				**Proportion (%) of**	
(mm)	**tagged fish**	**all fish**		**repeatedly recaptured**		**stayers**	**movers**
		n	**%**	**1x**	**2x**		
70-100	41	1	2.44	1	0	100	0
101-150	112	6	5.36	6	0	100	0
151-200	120	23	19.17	20	3	86.96	13.04
201-250	143	24	16.78	22	2	91.67	8.33
251-300	110	20	18.18	16	4	80	20
301-350	72	20	27.78	18	2	90	10
351-400	38	4	10.53	4	0	100	0
401-450	18	3	16.67	3	0	100	0
451-500	16	3	18.75	3	0	100	0
501-550	11	0		0	0		
551-600	2	0		0	0		
Total	683	104		93	11		

Table 1.5. Distribution of mobile barbel (*Luciobarbus bocagei*) according to the direction and distance of movement.

Distance from	Fish recaptured downstream		Fish recaptured upstream	
home section (m)	**N**	**%**	**N**	**%**
0-1000	4	36.36	3	27.27
1001-2000	2	18.18	0	0
2001-3000	0	0	0	0
3001-4000	0	0	1	9.09
4001-5000	0	0	0	0
5001-6000	0	0	1	9.09
Total	6	54.55	5	45.45

1.5. Discussion

The present study aimed to study potamodromous fish movements in a river segment affected by the presence of small barriers, using VIE tags. These VIE tags have proven applicable to a variety of purposes and suitable for different species, from insects (Moffatt, 2013) and crustaceans (Dinh et al. 2011), to equinoderms (Martinez et al. 2013), amphibians (Sapsford et al. 2014) and marine (Watt-Pringle et al. 2013) and freshwater fish (Reeves and Buckmeier 2009). Although widely used, these tags have seldom been applied in cyprinid field studies (but see: Goforth and Foltz 1998, Ficke and Myrick 2009, Pires et al. 2014). They guarantee a high retention rate and very low fish mortality rates (Roberts and Angermeier 2004; Curtis 2006; Skinner et al. 2006; Belica and Rahel 2008; Bolland et al. 2009; Ficke and Myrick 2009), and can even be used on small fish (Chapman and Warburton 2006, Hohn and Petrie-Hanson 2013). Results showed that although almost all recaptured barbel remained between barriers (residents), a portion of the population (11%) was able to volitionally move between segments by negotiating barriers in both upstream and downstream directions (migrants). In addition, there were no differences in fish size between migrants and residents. Iberian barbel have successively shown in laboratorial experiments that it is positively rheotactile and motivated to navigate fishways (Alexandre et al. 2013; Branco et al. 2013a, 2013b; Santos et al. 2013, 2014), negotiate small weirs (Amaral et al. 2016) and volitionally displace themselves along a flume (Branco et al. 2016). The results of this work further evidence that although barbel are able to negotiate small barriers, even with unfavourable barrier permeability and contrary to our hypothesis, they apparently prefer not to move over such obstacles. It seems plausible that small barriers introduce a resistance to movement and create migration friction. It has been proposed that a similar species, *Barbus barbus* (Peňáz et al. 2002; Vilizzi et al. 2006), has a metapopulation structure with a fragmented distribution. As in the present study, the population fragmentation of this species was marked as a result of the presence of locks and weirs – structures known to hinder *B. barbus* movements during spawning migration (Baras et al. 1994) – that promoted the separation of population components. Having said this, movements of *B. barbus* are associated with higher discharges (Lucas 2000), being the species capable of negotiating submerged weirs (Vilizzi et al. 2006). In a study similar to the present one

(Peňáz et al. 2002), the movements of *B. barbus* in a non-fragmented 3-km-long river stretch were evaluated, where river discontinuities were promoted by negotiable riffles. These authors also found that the majority of the population (70.5%) exhibited residency behaviour, and that the majority of the fish which moved (93.2%) did so over short distances – < 1000 m – and did not demonstrate any preferences in movement direction. The results of the present study – that there was no evidence of movement by the largest fish – and the fact that barbel are typical pool-dwellers (Santos et al. 2011), suggest that such residency reflects larger individuals' greater competitive ability in deeper mesohabitats between barriers (mostly pools and runs). Although few fish were able to negotiate the barriers, the individuals that moved the most were probably upstream- oriented migrating fish, as previously reported for a similar, albeit weir-free, river segment (Peňáz et al. 2002). Such results point to the existence of an effect of a migrating stimulus that pushes fish further upstream.

Whenever the movements of populations of migratory fish are hampered by barriers, they can cease to be migratory and change their life strategy to become resident populations, on condition that adequate spawning grounds are present between barriers – a hypothesis that has already been advanced by Branco et al. (2012). Additionally, there is increasing awareness that some migratory fish populations include a proportion of individuals that are non-migrant – a phenomenon called “partial migration” (Chapman et al. 2012a). Contrary to the “Restricted Movement Paradigm” (Gerking 1959; Rodríguez 2002), the partial migration theory states that the populations of many freshwater fish species are composed of both sedentary and mobile individuals (“Behavioural Dichotomy Model” (Smithson and Johnston 1999)), and by individuals that alternate between these behaviours in order to augment fitness (Knaepkens et al. 2005). This within-population migratory dichotomy may be extremely important to the resilience of freshwater fish populations (Stott 1967; Smithson and Johnston 1999; Larson et al. 2002), and appears to be much more present in such populations (Chapman et al. 2012a; Chapman et al. 2012b) than formerly perceived (Jonsson and Jonsson 1993). Partial migration may also explain why the impact of connectivity infringement on potamodromous species has been difficult to ascertain (Magoulick 2000; Pont et al. 2007). Peňáz et al. (2002) considered barbel (*B. barbus*) to be wandering fish, with most populations having a migratory and a resident portion, and this also seems to be supported by our results. The occurrence of large-scale disturbances such as climate change is expected to cause significant changes in the partial migration of potamodromous fish. According to the Intergovernmental Panel on Climate Change, it is expected that overall average annual temperatures in Southern Europe will increase by up to 4 °C by the end of the century, along with a decrease of 6% to 36% in river flow (IPCC 2007). Given that river temperatures are environmental correlates of air temperatures, this will have serious implications for aquatic biological processes, such as fish swimming performance and the ability to pass partial instream barriers (Kemp et al. 2011). Accordingly, the fact that the impact of barrier connectivity infringement may be further enhanced during low-flow periods means that one can expect a shift in the demographic balance between migrants and residents, towards a higher proportion of the latter.

In the present study, results point to a possible selection of certain behavioural phenotypes. If this were to be the case, barriers could be labelled as one of the important variables in shaping populations and communities. The formerly barrier-free population of barbel in the Alviela River may have begun as a partial migration population in which, by introducing a friction in migration and a resistance to movements, the added barriers selected the behavioural phenotype that promotes residency. This can be understood as an artificial population selection culminating in a population adaptation to the presence of barriers. The hypothesis that small barriers promote residency in potamodromous cyprinids can thus be raised. Hypothesis development is, and has been, at the centre of the scientific process and the publication of theories derived from preliminary data allows the reader to take part on the early steps of the scientific process (Rosenfeldt 2003). Even though scientific articles tend to focus on hypothesis testing, the formulation of a theory/hypothesis was once the standard in science journals. In fact, a theory that leads to research questions has “an autonomy of its own and is not the summation of existing empirical research” (Kilduff 2006) progressing science a step further, a step that needs confirmation, but forward nonetheless.

Although mark-recapture approaches are the most common technique for investigating movements of freshwater fishes in their natural habitat (Quintella et al. 2005), the findings of the present study should be viewed with care, since the low tag recovery rate (< 20%) means they only give us an ecological snapshot of part of the barbel population (Castro-Santos et al. 1996; Ruetz et al. 2015). The migration and residency costs and benefits affecting a given fish population should also be evaluated to understand whether fish fitness is maximized by incurring a migratory process or by increasing residency. Climate change will have severe impacts on hydrology, and most of the research on this subject to date has focused on diadromous species (Crozier et al. 2008; Lassalle and Rochard 2009; Finstad and Hein 2012; Piou and Prévost 2013), neglecting potamodromous fish (Beatty et al. 2014). Enhancing the knowledge of such impacts on potamodromous fish would further the understanding of the susceptibility of freshwater communities to climate-change-induced hydrological alterations (Beatty et al. 2014). The combination of barriers and reduced river flows caused by climate change will negatively affect longitudinal connectivity, imperilling the ability of such systems to deal with future events. Fully connected rivers are expected to have a high resilience to climatic variations, compared to regulated systems (Palmer et al. 2008). Future investigations on the impacts on freshwater fish of hydrological alterations resulting from climate change are thus needed. Further studies employing telemetry techniques (e.g. radio-telemetry and EMG-telemetry) that allow a finer and more dynamic time resolution of movement data, and thus discriminate between standard cyclic movements and true migrations, should be pursued. Such studies should ideally focus on different populations of the same fish species in connectivity-impacted and non-impacted sites, in order to disentangle the impact of small barriers on fully and partial potamodromous populations.

1.6. Conclusions

The results of this study show that barbel are able to negotiate barriers that fragment river systems. Movements were performed without any preferred directionality, and fish that moved did not differ in size from the fish that stayed between the same two barriers. Having said this, the majority of recaptured fish did not move, indicating that by increasing friction to migratory movements, barriers may promote an artificial selection of behavioural phenotypes that favour residency and thus induce a population adaptation to the presence of barriers. A hypothesis can be raised: River barriers may increase residency in potamodromous cyprinids.

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III. Small Broad–Crested Weirs

1. Upstream passage of potamodromous cyprinids over small weirs: the influence of key-hydraulic parameters

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1.1. Abstract

The presence of small weirs, far more numerous than dams, has increased habitat fragmentation on rivers worldwide. This study aims to evaluate the upstream passage performance of a potamodromous cyprinid, the Iberian barbel (*Luciobarbus bocagei*), over an experimental broad-crested weir by varying key-hydraulic parameters. Fish passage success was studied for different combinations of waterfall height (H), plunge pool depth (D) and flow discharge (Q). The flow pattern downstream of the weir was characterized with a 3D Acoustic Doppler Velocimeter, to assess the effects of hydrodynamics on fish behaviour. D, H, and their interaction D × H as well as Q were correlated with the number of successful upstream fish passes. However, counter-intuitively, higher fish passage success did not occur at combinations of lower H and Q, and higher D. Therefore, upstream fish passage appears to be a complex phenomenon, which is strongly dependent on the hydraulic environment that is produced by the interaction of these parameters. The outcomes of this work will help engineers and biologists to establish design criteria for requalification of small barriers in order to improve fish passage and habitat connectivity.

1.2. Introduction

River fragmentation caused by the presence of instream obstacles is considered one of the main threats to the sustainability of fish populations, being responsible for the decline or even extinction of populations through demographic, environmental and genetic stochasticity (Aarts et al. 2003; Nilsson et al. 2005). Nevertheless, barriers to fish migration occur not only through the presence of large dams and small hydropower plants, which have recently increased as a result of the promotion of renewable forms of energy (Santos et al. 2006; Crook et al. 2015), but also mainly through other artificial obstacles such as small weirs (Lucas and Baras 2001; O'Hanley 2011). These obstacles, that are in general less than 5 m in height (ONEMA 2010; Solà et al. 2011) and are considered to be 2–4 orders of magnitude more numerous than large structures (Lucas et al. 2009), alter the velocity patterns and the water depth, creating vertical drops that change the hydrodynamics of aquatic systems and may prevent the movement of fish species and hence their access to spawning, feeding and rearing areas (Leaniz 2008; Branco et al. 2012). However, compared with large regulated schemes, the effects of small weirs and natural obstacles are less well quantified, thus deserving greater attention not only due to their higher number (in the Portuguese Tagus basin alone, there are more than 2000 small weirs), but also because they can have a significant effect on fish movements, thereby potentially causing changes in the composition and structure of assemblages (Ovidio and Philippart 2002; Poulet 2007; Ordeix et al. 2011). This is in accordance with recent research lines and European projects, which emphasize the need for additional scientific studies to address the impact of small barriers on fish passage success (Harford and McLaughlin 2007; Klauer et al. 2012; Reyjol et al. 2014).

Previous studies on the upstream passage of small weirs have been mainly focused on salmonid species (e.g. Brandt et al. 2005; Lauritzen et al. 2005; Kemp et al. 2006; Kondratieff and Myrick 2006; Ovidio et al. 2007) and have shown that fish capacity to negotiate these obstacles is not only related to their swimming and jumping performance, but also with obstacle design and hydrodynamic conditions downstream of the weir (e.g. waterfall height, weir slope, plunge pool depth, flow discharge, turbulence). In this respect, the plunge pool depth (water depth below the weir) and waterfall height (distance from the plunge pool surface to the top of the weir crest) emerged as the two most important variables influencing fish movements in broad-crested weirs, which are typically constructed with a vertical downstream face from reinforced concrete, spanning the full width of the river channel (Baudoin et al. 2014).

The effect of plunge pool depth and waterfall height on the successful passage of fish has been investigated to improve knowledge on more effective upstream passage of fish. For example, analysing the ratio of plunge pool depth/waterfall height, Stuart (1962) found that for brown trout (*Salmo trutta*), Atlantic salmon (*Salmo salar*) and Euroasian minnow (*Phoxinus phoxinus*), successful passage occurred for a 1.25 ratio, while Lauritzen et al. (2005), for sockeye salmon (*Oncorhynchus nerka*), reported successes in ratios ranging from 0.68 to 1.53. On the other hand, Ovidio and Philippart (2002) assessed the impact of 28 small weirs on the upstream movements of six fish species, and focused on the need of a minimum plunge pool depth for a successful negotiation, postulating that water depth downstream of the obstacle should be at least “twice the size of the fish”. Kondratieff and Myrick (2006), and more recently Ficke et al. (2011), also highlighted the importance of plunge pool depth suggesting a minimum threshold not lower than 10 cm, to avoid inhibition of fish movements and minimize predation risk. It is clear that the effect of both plunge pool depth and waterfall height on upstream fish movements needs to be further addressed to quantify fish jumping performance and thus set guidelines for appropriate fish passage designs. This is particularly important for cyprinid fishes that are by far the dominant group of autochthonous freshwater fish in the Iberian Peninsula (Santos et al. 2011; Branco et al. 2014), and for which performance effectiveness in negotiating small weirs is virtually unknown.

The goal of this study is to evaluate the performance of upstream fish movements over a small experimental broad-crested weir adjustable for different plunge pool depths (D) and waterfall heights (H), under different flow discharges (Q). The conditions tested are representative of those that fish are expected to overcome when migrating upstream to spawn. Iberian barbel (*Luciobarbus bocagei*) was selected as the target species, since it is considered representative of at least eight species of medium-sized benthic potamodromous cyprinids in Iberia and Western Europe, counting the genera

Barbus and *Luciobarbus* (Santos et al. 2014). It was hypothesized that passage success would increase with decreasing waterfall heights in association with increasing plunge pool depths and low flow discharges.

1.3. Materials and methods

1.3.1. Fish and experimental facility

Adult Iberian barbel used in the experiments (n = 380; mean total length (TL) ± standard deviation (SD) = 18.7 ± 3.3 cm) were captured in the Lisandro River, a small Atlantic coastal river. Sampling was performed by wadable electrofishing (Hans Grassl IG-200) according to the protocol adopted by the European Committee for Standardization (CEN 2003). Six electrofishing episodes were performed (one episode per week), collecting 65 fish per episode. Fish were transported to the laboratory facilities, at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in a fish transport box (Hans Grassl, 190 L) with external aeration. At LNEC, fish were maintained for a maximum period of six days in filtered and aerated acclimation tanks (700 L tanks; Fluval Canister Filter FX5). To ensure high water quality levels in the acclimation tanks, water temperature (22 ºC ± 1 ºC), pH (≈ 7.3) and conductivity (215 ± 37 μS.cm^{-1}) were monitored every day using a multiparametric probe (HANNA, HI 9812-5). Water replacement was performed daily with a turnover rate of 150 L.day^{-1}. Feeding (Tetra Pond sticks) stopped 24–48 h prior to the experiments.

Experiments were conducted in an indoor experimental ecohydraulic channel installed at LNEC. The channel (Figure 1.1A) consists of a rectangular steel frame (10.0 m long × 1.0 m wide × 1.2 m high) with glass-viewing panels on sidewalls that allow free observation of fish within the flume. The facility includes an upstream and a downstream tank, separated from the flume by mesh panels, from where the water enters the flume and is recirculated. The channel was tilted at a 3% slope, determined to be representative of central and southern Iberian rivers according to the European River and Catchment Database (Catchment Characterization and Modelling, version 2 [CCM2]; Vogt et al. 2007). Water quality in the flume was also monitored after each experiment. No difference was registered between water temperature in acclimation tanks and in the flume (22 ºC ± 1 ºC); values of pH and conductivity were of ≈ 8.3 and 172 ± 22 μS.cm^{-1}, respectively.

1.3.2. Testing plunge pool depths and waterfall heights

To study the effects of plunge pool depths and waterfall heights on upstream passage of Iberian barbel, an experimental broad-crested weir made of polyvinyl chloride (PVC) modules was tested for a factorial design of 16 combinations (Table 1.1) considering four different plunge pool depths (D = 10, 20, 30, 50 cm), and four waterfall heights (H = 5, 10, 15, 25 cm). Minimum plunge pool depth was difficult to set up because it depends on the size and swimming capabilities of fish, and how the plunging jet dissipates downstream of the weir (Baudoin et al. 2014). Nonetheless, for large rheophilic cyprinids, these authors propose a water depth of 10 cm as the minimum to overcome an obstacle, which was therefore the threshold selected for the present study. Maximum waterfall height for the current experiments was determined by carrying out preliminary studies. A lower waterfall height (5 cm) was used initially and, in subsequent trials, fish were presented with increasing heights (5 cm increments) until no fish could negotiate the weir. This final height was taken to be the critical weir height. The maximum waterfall height used in the trials was the critical weir height plus 5 cm. Once the maximum waterfall height was determined, trials were assigned randomly, resulting in ratios of D/H that ranged from 0.4 to 10.

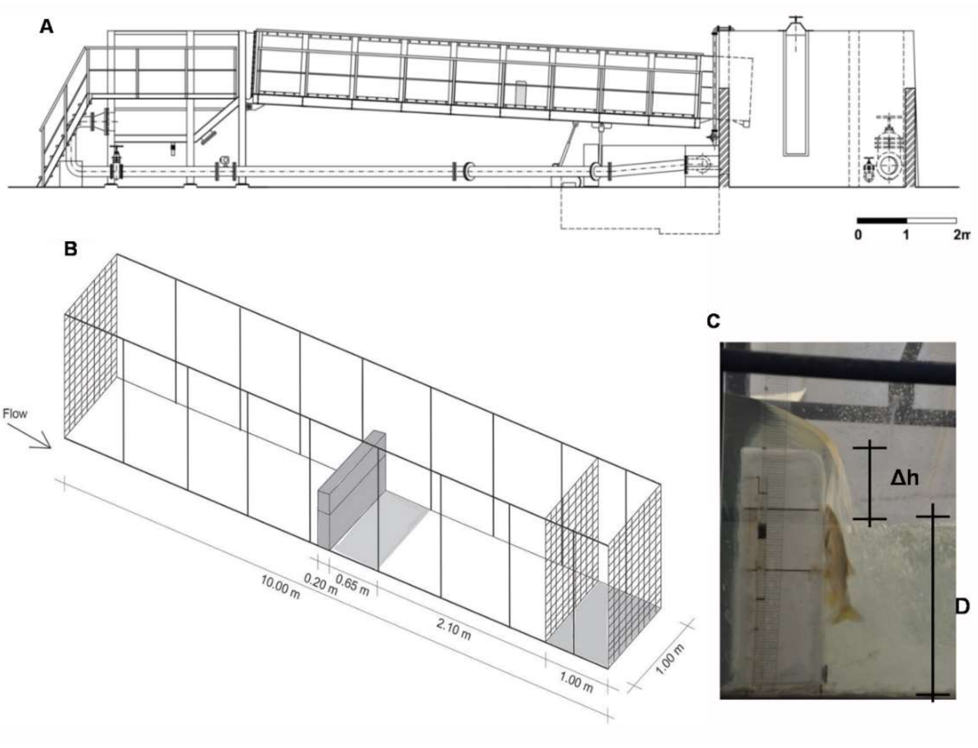

Fig. 1.1. Representation of (A) side view of the experimental channel on a slope of 3%; (B) three-dimensional scheme of the experimental ecohydraulics flume showing the location of the experimental weir (2.75 m upstream of the acclimation area), the acclimation area (1 m^2 area shown shaded between the two removable fine mesh panels located downstream), and the approach area (0.65 m^2 shaded area immediately downstream the weir); and (C) experimental broad-crested weir, considering the plunge pool depth (D – distance from the bottom of the flume to the top of the water surface) and waterfall height (H – distance from the water surface to the top of the crest of the experimental weir). This picture provides a visible attempt by fish to swim up the skimming flow formed in the downstream face of the weir.

Table 1.1. Tested plunge pool depths and waterfall heights (D × H) in the experimental weir to assess upstream passage performance of Iberian barbel.

		Waterfall heights (cm) – H			
		H05	H10	H15	H25
Plunge pool depths (cm) – D	D10	D10H05	D10H10	D10H15	D10H25
	D20	D20H05	D20H10	D20H15	D20H25
	D30	D30H05	D30H10	D30H15	D30H25
	D50	D50H05	D50H10	D50H15	D50H25

The experimental weir (Figure 1.1B) spanned the entire channel width, with a constant thickness of 20 cm, and it was installed in the flume at 2.75 m upstream of the acclimation area, which was created in the downstream zone of the flume by two mesh panels 1 m apart. Immediately downstream of the weir, a 0.65-m long zone was considered as the approach area. Flow discharge was measured by a flow meter installed in the supply pipe and maintained equal to 50 L.s^{-1}. The different waterfall heights (Figure 1(C)) were set up by adding or removing modules from the weir. The plunge pool depth below the weir was controlled by a gate located at the downstream tank of the channel.

Before each trial, fish were held 15 minutes in the acclimation area to allow adaptation to the flume conditions. After that period, the upstream mesh panel was removed and fish were allowed to volitionally explore the channel for 60 minutes. Both upstream and downstream passes were allowed, so that fish could negotiate the weir multiple times. Each combination tested had four replicates carried out with schools of five fish for each replica. Each fish was used only once and was randomly selected. Fish movements were monitored by direct observation and recorded by a video camera (GoPro HERO3). Registered observations included number of fish that approached the weir (Ap; fish that entered the approach area), number of passage attempts (At; fish that actively tried to negotiate the waterfall), number of passage successes (N), and time taken to achieve the first successful upstream passage (T; min). At the end of each trial, fish were measured (TL ± 0.1 cm) and water temperature and quality (pH and conductivity) in the flume were monitored. All trials were performed during late spring and early summer, in the morning period (07–13h) so that environmental conditions, such as temperature and light, were fairly constant throughout the experiments.

1.3.3. Effects of flow discharge on upstream movement of fish

To study the effects of flow discharge on barbel capacity to successfully negotiate a small weir, three additional discharges were tested: 25, 75 and 100 L.s^{-1}. These discharges were tested with the combination of waterfall height and plunge pool depth that previously showed the highest passage success with 50 L.s^{-1} and also followed the procedures previously described.

1.3.4. Hydrodynamics characterization

To characterize the hydrodynamic conditions downstream of the weir, the three components of flow velocity (x, y, z) were measured with a downward-looking 3D Acoustic Doppler Velocimeter (Vectrino ADV; Nortek AS). A grid with 27 sampling points was implemented at the center of the flume, assuming flow symmetry across its width. The sampling points were established according to the expected velocity field variation and taking into account the limitations of the ADV equipment. Such limitations included the minimum distance required at the bottom of the flume (5 cm) and near the obstacle, as well as the need for the probe to be completely immersed during the data acquisition period. This was difficult to ensure near the weir for some combinations due to turbulence derived from the energy dissipation of the plunging jet downstream the weir. Water velocity data were acquired at a sampling rate of 25 Hz for a period of 180 s. The combinations characterized were the one that registered a lower passage success; the combination expected to achieve the best passage results; and the combination that actually provided the best results.

1.3.5. Data analysis

To determine the potential negotiation of the weir for the combinations tested, similarly to studies on efficiency of fishways (Bunt et al. 1999; Lucas and Baras 2001; Aarestrup et al. 2003; Calles and Greenberg 2009), the percentage of attraction efficiency (AE) and the percentage of passage efficiency (PE) were calculated from Equations (1) and (2).

$$\text{AE \%} = 100 \times \frac{\text{number of fish that attempted to negotiate the weir}}{\text{number of fish that entered the approach area}} \tag{1}$$

$$\text{PE \%} = 100 \times \frac{\text{number of successful passages}}{\text{number of fish that attempted to negotiate the weir}} \tag{2}$$

To determine the influence of plunge pool depths, waterfall heights and their interaction (D × H) on the number of successful upstream passes of Iberian barbel, a distance-based MANOVA (PERMANOVA) using the Euclidean distance was performed by using PCORD 6 (Peck 2010). Likewise, to test the effect of flow discharge on the successful negotiation of the weir, a Kruskal–Wallis ANOVA with a post hoc Dunn’s test for pairwise comparison was performed by using the dunn.test package (Dinno 2015) from the open-source software R (R Core Team 2014).

Data on instantaneous velocity (V_i) were filtered with WinADV freeware software (Wahl 2001) using the Goring and Nikora (2002) phase-space threshold despiking method, modified by Wahl (2003). Then, to analyse velocity fluctuations and turbulence gradients along the water column in a vertical plane, the resultant V_{xz} and turbulent kinetic energy (TKE; important turbulence descriptor (Wang and Hartlieb 2011; Wilkes et al. 2013) in ecohydraulic studies) were calculated and represented graphically, by vector and contour maps, to illustrate the hydrodynamic conditions within the test area (e.g. areas of high velocity and turbulence gradients) that might have affected fish movements. Additionally, for the tested discharges, differences in flow velocities and turbulence were analysed using a non-parametric Friedman test followed by a Nemenyi post hoc test applying the R package PMCMR (Pohlert 2015).

1.4. Results

1.4.1. Plunge pool depths and waterfall heights

Fish attempted to negotiate all D × H tested combinations (Table 1.2) (an example of a successful attempt is illustrated in Figure 1.1C). However, successful upstream passage, as well as the number of fish approaches, the number of attempts to pass the weir, and the time needed to successfully pass upstream, was markedly variable among combinations. Overall, a total of 254 upstream successful passages were registered for all combinations of D × H. Regarding the approach movements and attempts to pass the weir, an average of 710 approaches (max = 1013 approaches, in D50H15; min = 293, in D10H25) and 183 attempts (max = 328 attempts, in D30H05; min = 65, in D10H05) were recorded.

Table 1.2. Combinations of plunge pool depths and waterfall heights tested (D × H). D/H, plunge pool depth/waterfall height ratio; Q, flow discharge (L.s^{-1}); n, number of fish tested; Ap, total number of approaches; At, total number of attempts to pass the weir; N, total number of successful passages; %AE, percentage of attraction efficiency (ratio of the number of attempts per number of approaches × 100); %PE, percentage of passage efficiency (ratio of successful passages per number of attempts × 100); T, mean time until the first successful passage (min).

D × H	D/H	Q	n	Ap	At	N	%AE	%PE	T
D10H05	2	50	20	774	65	10	8	15	33
D10H10	1	50	20	733	138	11	19	8	29
D10H15	0.67	50	20	765	90	18	12	20	15
D10H25	0.40	50	20	293	72	1	25	1	46
D20H05	4	50	20	687	183	9	27	5	22
D20H10	2	50	20	548	291	50	53	17	15
D20H15	1.33	50	20	943	248	24	26	10	17
D20H25	0.80	50	20	746	173	19	23	11	33
D30H05	6	50	20	682	328	17	48	5	15
D30H10	3	50	20	650	299	28	46	9	24
D30H15	2	50	20	525	204	9	39	4	24
D30H25	1.20	50	20	715	110	3	15	3	13
D50H05	10	50	20	734	196	25	27	13	24
D50H10	5	50	20	676	146	8	22	5	20
D50H15	3.33	50	20	1013	171	18	17	11	9
D50H25	2	50	20	885	210	4	24	2	26

The best results were achieved for the combination of D20H10 (D/H = 2), with 50 successful passages and a PE of 17%. This percentage of PE was only surpassed by combination D10H15 (D/H = 0.67; 20%); however, in D10H15, both the number of attempts (90) and the number of successful passages (18) were lower than D20H10. Additionally, combination D20H10 registered the highest percentage of AE (53%), with a total of 548 approaches that resulted in 291 attempted movements. Having the same D/H ratio as combination D20H10, D/H = 2, combinations D10H05, D30H15 and D50H25, however, recorded very different passage successes (10, 9, and 4 upstream passages, respectively) and the percentages of AE and PE were also lower compared with the results of combination D20H10.

The poorest results were registered for combination D10H25 (D/H = 0.4), with only one successful upstream passage and a PE of 1%. This combination registered also the lowest number of approaches, a total of 293, and only 72 attempts. Moreover, it actually registered the highest time until the first (and single one) successful passage occurred (46 min). Combination D50H05 (D/H = 10), which was expected to provide the best results due to its higher plunge pool depth in association with a lower waterfall height to overcome, only ranked third with 25 successful passages, 27% of AE, and 13% of PE.

Results of the PERMANOVA analysis showed significant effects of D (*F* = 5.46; *P* = 0.004), H (*F* = 4.68; *P* = 0.006), and the interaction D × H (*F* = 3.02; *P* = 0.005) on the number of successful upstream fish passage events. Pairwise comparisons (Table 1.3) performed for each factor showed that the number of successful fish movements past the weir was significantly different, and higher, for D = 20 cm, in relation to the other tested plunge pool depths. On the contrary, for the tested waterfall heights, H = 25 cm was significantly different, registering the lowest number of successful movements.

Table 1.3. Pairwise comparisons, after the main test (PERMANOVA), on the number of successful fish movements for factors: plunge pool depths (D) and waterfall height (H). Bold values highlight significant differences. α = 0.05.

Factor	Pairwise comparisons	Results	
		t	*P*
D	**D10 vs. D20**	3.05	**<0.01**
	D10 vs. D30	1.73	0.094
	D10 vs. D50	1.34	0.197
	D20 vs. D30	2.05	**<0.05**
	D20 vs. D50	2.07	**0.05**
	D30 vs. D50	0.14	0.871
H	H05 vs. H10	1.88	0.070
	H05 vs. H15	0.55	0.572
	H05 vs. H25	2.63	**<0.05**
	H10 vs. H15	1.32	0.192
	H10 vs. H25	3.47	**<0.01**
	H15 vs. H25	2.67	**<0.05**

1.4.2. Flow discharge

The number of successful upstream passages, as well as fish approaches and attempts to pass the weir, was found to decrease with the increment of flow discharge (Table 1.4). The largest number of attempts (total of 291) and successful passages (50) were registered for 50 $L.s^{-1}$. On the contrary, the discharge of 100 $L.s^{-1}$ proved to be the most limiting for fish, registering only 26 approaches and 12 attempts to negotiate the weir, which resulted in a single successful passage almost at the end of the trial (57 min). For 25 $L.s^{-1}$, there were a high number of fish approaches (a total of 1440), but resulted in only 280 attempts leading to a low AE (19%). PE was also low due to the small number of successful passages (14). Results of the Kruskal-Wallis test show that flow discharge significantly affected the number of successful passages of barbel (H = 10.95; 3 *d.f.*; P = 0.01). Further, Dunn's multiple comparison test (Table 1.5) revealed that for 100 $L.s^{-1}$, the number of successful passes was significantly lower than for 25 $L.s^{-1}$ and especially for 50 $L.s^{-1}$. Likewise, successful passes for 75 $L.s^{-1}$ were also significantly lower compared to the ones that occurred for 50 $L.s^{-1}$.

1.4.3. Hydrodynamics

Figures 1.2 and 1.3 display the variation of TKE and flow velocity, respectively, for the different conditions tested. Contour maps revealed that both TKE values (Figure 1.2A,B,D,E) and velocity (Figure 1.3A,B,D,E) increased with flow discharges. This increase was particularly important in the case of 75 $L.s^{-1}$, where values of TKE above 1 $m^2.s^{-2}$ and velocity just above 1 $m.s^{-1}$ were registered close to the foot of the weir, and for the 100 $L.s^{-1}$ which also registered similar values, although these were located furthest from the weir. For combinations D20H05 (Figure 1.2C and Figure 1.3C; that registered a lower passage success) and D50H05 (Figure 1.2F and Figure 1.3F; combination that was expected to achieve the best passage results), values of TKE and velocity were slightly higher when compared with D20H10 (Figure 1.2B). Statistical analysis of hydraulic characterization of combinations D20H10, D20H05, and D50H05, demonstrate that there were significant differences among their respective V_{xz} (Fr = 11.76; 2 *d.f.*; P < 0.01) and TKE values (Fr = 7.44; 2 *d.f.*; P < 0.05). Regarding the flow discharges tested in combination D20H10, results of Friedman tests revealed that the four flows were significantly different both in terms of velocity (Fr = 53.73; 3 *d.f.*; P < 0.001) and TKE (Fr = 78.03; 3 *d.f.*; P < 0.001); nevertheless, results of pairwise comparisons for the parameter velocity show that there were no significant differences for 25 $L.s^{-1}$ vs. 50 $L.s^{-1}$ (P = 0.46).

Table 1.4. Experimental designs to test the influence of flow discharge on the jumping performance of Iberian barbel. D × H, tested combination; Q, flow discharge ($L.s^{-1}$); n, number of fish tested; Ap, total number of approaches; At, total number of attempts to pass the weir; N, total number of successful passages; %AE, percentage of attraction efficiency (ratio of the number of attempts per number of approaches × 100); %PE, percentage of passage efficiency (ratio of successful passages per number of attempts × 100); T, mean time until the first successful passage (min). Results from Q = 50 $L.s^{-1}$ are the same as presented in Table 1. They are presented here for ease of comparison.

D × H	Q	n	Ap	At	N	%AE	%PE	T
D20H10	25	20	1440	280	14	19	5	27
	50	20	548	291	50	53	17	15
	75	20	208	66	8	32	12	40
	100	20	26	12	1	46	8	57

Table 1.5. Pairwise comparisons (Dunn's post hoc test), after the main test (Kruskal-Wallis), on the number of successful fish movements for factor flow discharge (Q). Bold values highlight significant differences. α = 0.05.

Factor	Pairwise comparisons	Results	
		Z	*P*
Q	Q25 vs. Q50	1.20	0.11
	Q25 vs. Q75	-0.86	0.19
	Q25 vs. Q100	-1.99	**0.02**
	Q50 vs. Q75	-2.07	**0.02**
	Q50 vs. Q100	-3.19	**<0.001**
	Q75 vs. Q100	-1.13	0.13

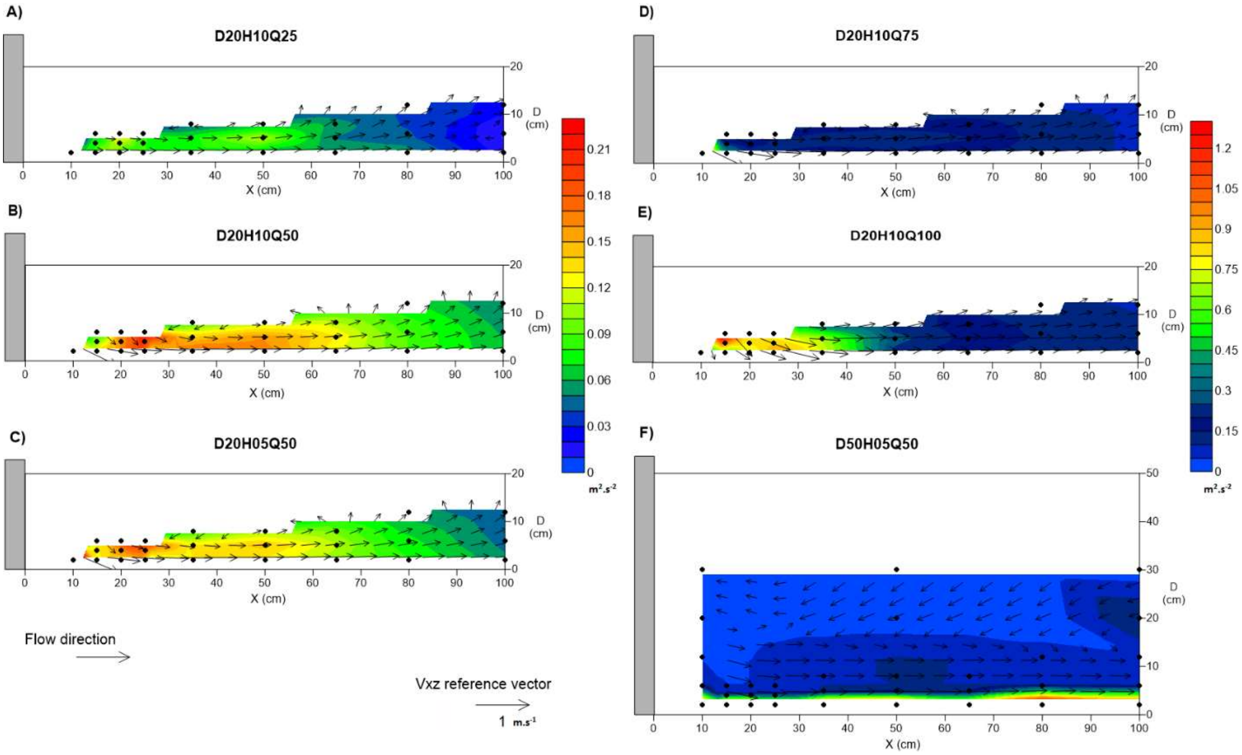

Fig. 1.2. Graphical representation of turbulent kinetic energy (TKE; $m^2.s^{-2}$) and velocity vectors (V_{xz}; $m.s^{-1}$) for combinations tested: (A) D20H10 with 25 $L.s^{-1}$; (B) D20H10 with 50 $L.s^{-1}$; (C) D20H05 with 50 $L.s^{-1}$; (D) D20H10 with 75 $L.s^{-1}$; (E) D20H10 with 100 $L.s^{-1}$; and (F) D50H05 with 50 $L.s^{-1}$. X is the distance from the weir (cm) and D is the water depth (cm). Points represent the measuring mesh.

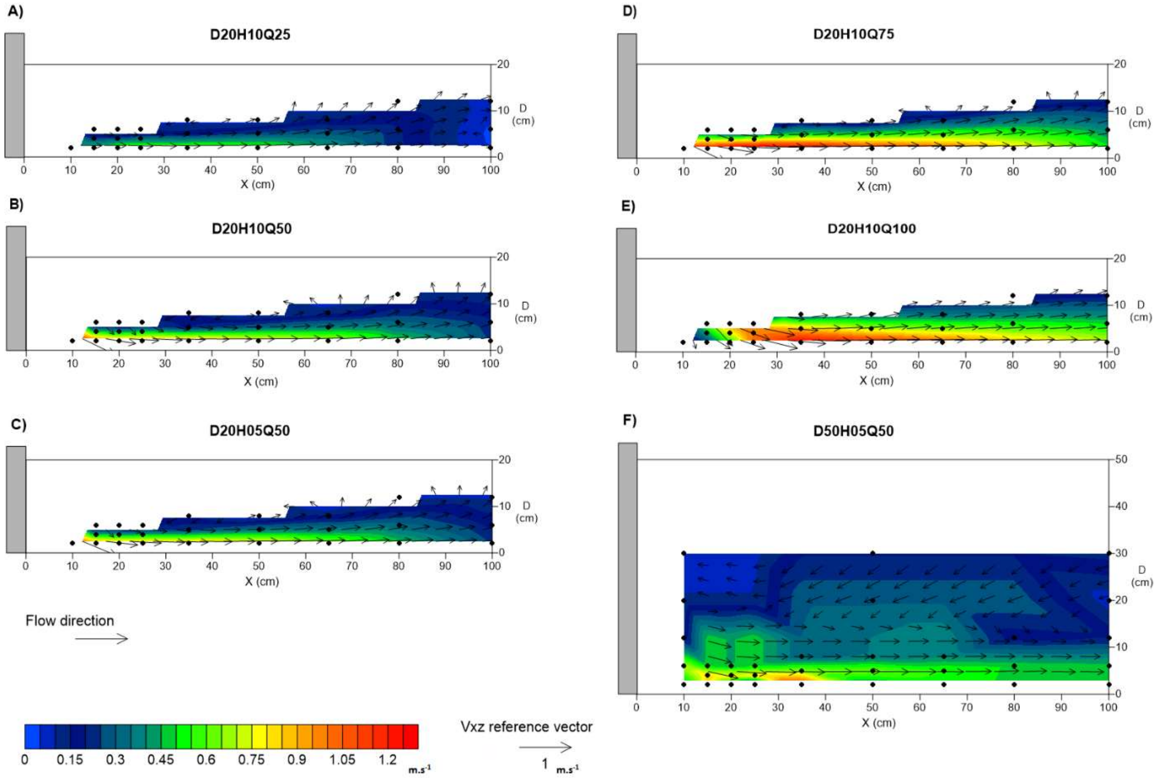

Fig. 1.3. Magnitude and direction of water velocity (V_{xz}; $m.s^{-1}$) in combinations tested: (A) D20H10 with 25 $L.s^{-1}$; (B) D20H10 with 50 $L.s^{-1}$; (C) D20H05 with 50 $L.s^{-1}$; (D) D20H10 with 75 $L.s^{-1}$; (E) D20H10 with 100 $L.s^{-1}$; and (F) D50H05 with 50 $L.s^{-1}$. X is the distance from the weir (cm) and D is the water depth (cm). Points represent the measuring mesh.

1.5. Discussion

This study highlights the importance of plunge pool depth, waterfall height, and flow discharge, as well as their interaction, for the successful negotiation of Iberian barbel over small broad-crested weirs. The high numbers of recorded movements (approaches and attempts) as well as passage successes demonstrated that Iberian barbel were stimulated to move upstream and negotiate the weir. Nevertheless, passage success varied among combinations, indicating that some of the combinations were more favourable for upstream passage as a consequence of suitable hydrodynamic conditions for fish (Liao 2007; Williams et al. 2012; Elder and Coombs 2015).

Similar to other studies (Brandt et al. 2005; Kondratieff and Myrick 2005; Kondratieff and Myrick 2006; Ficke et al. 2011), results from attraction efficiency, passage efficiency, and passage success recorded for D × H demonstrate that the combination of shallow plunge pool depths with high waterfall heights, which produce low D/H ratios, may inhibit the successful passage of Iberian barbel. Generating such unfavourable conditions, combination D10H25, which matched the smallest D/H ratio tested (D/H = 0.4), achieved only one successful upstream passage. However, for combination D10H15, the second smallest ratio tested (D/H = 0.67), and similar to the one reported by Lauritzen et al. (2005) as the minimum ratio to allow sockeye salmon to negotiate barriers, the number of passage successes increased to 18. Nevertheless, passage success did not always increase with increasing D/H ratios – for example, 28 successful passages were recorded for D/H = 3 (combination D30H10) and for D/H = 6 (combination D30H05) only 17 successes were achieved. Interestingly, and contrary to what might be expected, combination D50H05, which represented the maximum D/H ratio tested (D/H = 10), did not register the highest number of passage successes; it ranked only third.

Another interesting result was that for combinations with the same D/H ratio (D/H = 2 for D10H05, D20H10, D30H15 and D50H25), different numbers of passage success were recorded (N = 10, 50, 9, and 4, respectively). This highlights the fact that, combinations with the same D/H ratio generate different hydrodynamic patterns below the weir, thereby affecting the successful passage of fish over it. These results corroborate what was postulated by Baudoin et al. (2014) about the energy dissipation of the plunging jet downstream of a weir playing an important role on the attraction and, especially, on the passage success of fish. In fact, in combinations tested, values of PE were, in general, lower than AE estimates, pointing out that passage limitations are more severe than attraction limitations. Additionally to the jet energy dissipation, it should also be highlighted that the nappe shape, which depends on the specific flow discharge, and the amount of air entrainment also influence the successful negotiation of these obstacles. Furthermore, other aspects not considered in this study, like the plan shape of the weir and the downstream bottom irregularities, which influence the flow field characteristics (Pasternack et al. 2006; Vallé and Pasternack 2006; Wyrick and Pasternack 2008), may also play a role on the fish performance when negotiating small weirs.

The importance of jet dissipation, nappe profile and air entrainment were also evident in flow discharge tests implemented for combination D20H10. Fewer approaches, attempts to pass the weir, and successful passes were recorded with increasing flows and, in addition, fish also required more time to negotiate the weir. The highest number of passage successes was not achieved for the lowest discharge (25 L.s^{-1}), although an elevated number of fish approaches were recorded, which lead us to surmise that the plunging jet and the nappe formed in the downstream face of the weir (to vertical and shallow) were not sufficiently efficient to form an attractive path (see Powers and Orsborn 1985) to stimulate fish to negotiate the obstacle. On the other hand, for higher discharges (75 and 100 L.s^{-1}), the TKE values created by the plunging jet were high, with intensities above 1 m^2.s^{-2} registered close to the weir. High velocities (>1 m.s^{-1}) were also observed which, together with the high TKE and the consequent aeration, may have decreased the ability of fish to negotiate the weir, since cyprinids, like Iberian barbel, are shorter in length and generate lower speeds compared to salmonid species (Doadrio 2001; Silva et al. 2009; Alexandre et al. 2013; Katopodis and Gervais 2016).

This study showed that the successful passage of small vertical weirs by cyprinid species is a complex phenomenon where not only the plunge pool depth and waterfall height, which have been studied previously, especially for salmonids, are important. In addition, flow discharge also contributes to setting the most favourable hydrodynamic conditions for fish to overcome the obstacle. Some results were different to what might be expected from more simplistic assumptions, as some of the combinations that might have been predicted to be easily negotiated by fish turned out to be more difficult, leading to lower success of passage. This highlights the complexity and importance of the interaction of geometry and hydraulic parameters, as well as fish abilities, to successfully negotiate small obstacles. Although defining D/H thresholds for successful fish passage is important, both nominal values of each parameter should also be taken into account when designing or retrofitting weir like structures; otherwise their impact on river functional connectivity will not be improved as expected.

In nature, all the unfavourable conditions experienced in this study (shallow plunge pool depths, high waterfall heights, low flow discharges, high turbulence and air entrainment) commonly occur. These may lead to an increase in energy expenditures of fish during negotiation of the obstacles (Enders et al. 2005; Tritico and Cotel 2010) that may then reduce swimming performance and possibly cause disorientation (Pavlov et al. 2000; Liao 2007; Tritico and Cotel 2010) and fish fatigue (Katopodis and Gervais 2012). All these conditions may delay fish migration and/or reduce the number of fish that access important upstream habitats for spawning (in addition to other adverse effects; e.g. Ovidio and Philippart 2002; Castro- Santos and Haro 2003; Kemp and O'Hanley 2010; McLaughlin et al. 2013).

The outcomes of this work are expected to be useful to identify potential migration obstacles for potamodromous cyprinids and to define design criteria for the requalification of small barriers (Ovidio and Philippart 2002; Kondratieff and Myrick 2006), improving fish passage and consequently habitat connectivity, and population management (Meixler et al. 2009). Being a laboratory based study, it is recognized that the tested parameters and their respective interactions do not fully explain all the complex situations that fish can encounter in nature (e.g. temperature, noise, substrate roughness, weir geometry irregularities, channel complexity, cover, etc.). Furthermore, not all size classes of fish were tested, due to the burden that these experiments would represent (time, number of fish, laboratory conditions), and so, different behaviours and abilities may be expected in experiments, and in the field, with other size classes. However, fish used in the experiments were chosen within the range of 15–25 cm total length that represents the typical size class of natural adult fish, the most active size class in upstream migration of this and other medium-sized benthic potamodromous cyprinids found in Iberian and European river ecosystems (Kottelat and Freyhof 2007; Doadrio et al. 2011). Nevertheless, this work provided valuable insights that should be combined with in situ studies (Lauritzen et al. 2005; Pasternack et al. 2006; Ovidio et al. 2007; Kemp et al. 2011) to better understand how fish species respond to macro- and micro-hydrodynamic complex conditions downstream of barriers – what attracts them and what repels them. This is the key to enhance knowledge on negotiation of small instream obstacles by fish and to develop and design successful passage facilities (Williams et al. 2012).

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2. To swim or to jump? Passage behaviour of a potamodromous cyprinid over an experimental broad-crested weir

Amaral, S.D.; Branco, P.; Katopodis, C.; Ferreira, M.T.; Pinheiro, A.N.; Santos, J.M. 2018. To swim or to jump? Passage behaviour of a potamodromous cyprinid over an experimental broad-crested weir. River Research and Applications, 34: 174–182. https://doi.org/10.1002/rra.3232

2.1. Abstract

Physical stressors, such as man-made obstacles, are considered one of the main causes that negatively affect freshwater fish. Even small weirs may impact fish populations, including potamodromous cyprinids, by partially or totally blocking upstream migratory movements. Some studies have addressed the effect of key hydraulic parameters on upstream movements past small weirs, but little is known on how these parameters interact to induce swimming or jumping behaviour in negotiating such obstacles. This study aims to evaluate the passage behaviour (swimming vs. jumping) of Iberian barbel (*Luciobarbus bocagei*), a potamodromous species, over an experimental small broad-crested weir, considering the effect of different plunge pool depths (D), waterfall heights (H), and weir discharges (Q). Results revealed that passage behaviour was highly dependent on combinations of plunge pool depths and waterfall heights. Barbel navigated most configurations by swimming (overall outcomes: 81.5% swimming vs. 18.5% jumping), except the ones with the higher waterfall heights (25 cm) tested. Therefore, higher waterfalls proved to be preponderant in the switching of passage behaviour from swimming to jumping. Regarding the discharge over the 1-m-wide weir (overall outcomes: 85% swimming vs. 15% jumping), contrary to what was expected, there was no evidence that passage behaviour was discharge-related, for the range of discharges tested (25–100 L.s^{-1}). These results are useful to identify potential migration obstacles and should be taken into consideration in river restoration projects and when designing fishways for potamodromous cyprinids.

2.2. Introduction

Alterations in fish communities have been highly documented and strongly associated with physical stressors, such as man-made obstacles (Aarts et al. 2003; Branco et al. 2012; Crook et al. 2015). Even small weirs that could be considered a priori permeable to fish movements may negatively impact fish populations, by partially or totally blocking upstream migratory movements (Branco et al. 2017; King et al. 2017; Lucas et al. 2009; Meixler et al. 2009). Potamodromous cyprinid species are particularly affected by the loss of longitudinal connectivity due to their need to perform seasonal reproductive migrations (Baudoin et al. 2014; Branco et al. 2016; Doadrio et al. 2011; Lucas and Frear 1997) that are fundamental to complete their life cycle. In addition, the limited swimming and jumping capacity of mature cyprinids when compared to adult salmonids (Baudoin et al. 2014; Katopodis and Gervais 2016; Ovidio and Philippart 2002; Silva et al. 2009) further magnify the impacts of barriers.

In Iberian rivers, potamodromous cyprinids are the predominant fish fauna (Doadrio et al. 2011; Morán-López et al. 2006; Santos et al. 2011). The most usual passage behaviour of these species is to swim through the water nappe formed in the downstream face of small obstacles (Baudoin et al. 2014), as they are considered to be “non-jumping species” (Baudoin et al. 2014; Doadrio et al. 2011). As noted by Baudoin et al. (2014), several studies mention the presence of potamodromous cyprinids retained below small obstacles because of little motivation or inability to jump over such physical stressors. Nevertheless, Branco et al. (2017) studied the movements of Iberian barbel *Luciobarbus bocagei* in a river segment affected by the presence of small weirs and concluded that 11% of the tagged individuals moved between segments, negotiating the weirs either by swimming or jumping. Furthermore, Morán-López and Tolosa (2017) reported on the great ability of barbel (*Luciobarbus spp.*) to jump a maximum height of approximately 150 cm when trying to negotiate the Granadilla weir, located in the Guadiana River, 6.5 km upstream of the Spanish–Portuguese border. Thus, these studies seem to demonstrate that if suitable hydraulic conditions are found directly downstream of obstacles, potamodromous cyprinids may individually adapt their passage behaviour (swimming vs. jumping) to the local hydrodynamic scenario in their attempts to overcome barriers to reach upstream essential habitats (Branco et al. 2017; Lucas and Frear 1997; Morán-López and Tolosa 2017; Ovidio and Philippart 2002).

Several studies have addressed the effect of hydraulic parameters on the upstream passage success of fish over small weirs. Key parameters such as plunge pool depth, waterfall height, discharge, and consequently turbulence downstream of the obstacle have been identified as preponderant for successful upstream passage (Amaral et al. 2016; Ficke et al. 2011; Kondratieff and Myrick 2006; Ovidio and Philippart 2002; Stuart 1962). However, little is known on how these parameters interact to induce a swimming or a jumping behaviour in negotiating such obstacles, especially for potamodromous cyprinids.

This study aims to assess the interaction of the key parameters plunge pool depth (D; water depth below the weir), waterfall height (H; distance from the plunge pool surface to the top of the weir crest), and weir discharge (Q), associated to the switch in the upstream passage behaviour of Iberian barbel *L. bocagei*, from swimming to jumping, over an experimental broad-crested weir. Iberian barbel is a medium-sized benthic potamodromous cyprinid, considered representative of at least eight other species (from the genera *Barbus* and *Luciobarbus*) commonly present in Iberia and Western Europe rivers (Doadrio et al. 2011; Santos et al. 2014). It is expected that (a) passage behaviour (swimming vs. jumping) will differ according to the combinations of plunge pool depths and waterfall heights; (b) configurations with higher waterfalls will induce a jumping behaviour, whereas combinations with lower waterfalls will prompt swimming behaviour; and (c) passage behaviour will be discharge related, with higher discharges leading to a switch from swimming to jumping behaviours.

2.3. Materials and methods

2.3.1. Experimental facility

Experiments were conducted in an indoor experimental flume installed at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC). The rectangular steel frame flume (10.0 m long × 1.0 m wide × 1.2 m high) has glass sidewalls that allow unobtrusive observation of fish. The system is completed by an upstream tank, from which the water flows into the flume, and a downstream tank, where the water is recirculated (Figure 2.1A). Both tanks are separated from the flume by mesh panels. To represent the average slope of central and southern Iberian rivers, the flume was set at a 3% slope (Catchment Characterisation and Modelling, version 2; Vogt et al., 2007). Water quality in the flume was monitored after each trial using a multiparametric probe (HANNA, HI 9812-5). Values of water temperature (22 ± 1 ºC), pH (≈ 8.3), and conductivity (172 ± 22 µs.cm^{-1}) remained constant throughout the experiments.

An experimental broad-crested weir made of polyvinyl chloride modules was used to study the effect of D, H, and Q on the upstream passage behaviour (swimming or jumping) of Iberian barbel (Figure 1b). The experimental weir was installed in the flume at 2.75 m upstream of the acclimation area (area created by two mesh panels, 1 m apart on the downstream zone of the flume), spanning the entire channel width with a constant thickness of 20 cm.

2.3.2. Fish experiments

Three hundred eighty young adult Iberian barbels were used in the experiments (mean total length ± standard deviation = 18.7 ± 3.3 cm). Fish were captured in the Lisandro River, a small Atlantic coastal river, by electrofishing (Hans Grassl IG-200). Six electrofishing episodes were performed (one episode per week, collecting 65 fish per episode) according to the protocol adopted by the European Committee for Standardization (CEN, 2003). A fish transport box (Hans Grassl, 190 L) with external aeration was used to transport the fish to the laboratory facilities, at LNEC, where they were maintained in filtered and aerated acclimation tanks (700 L tanks; Fluval Canister Filter FX5) for a maximum period of 6 days. During that period, fish were fed with Tetra Pond sticks up to 24–48 hr prior to the experiments. Water quality in the acclimation tanks was also monitored (temperature, pH, and conductivity of 22 ± 1 ºC, ≈7.3, and 215 ± 37 µs.cm^{-1}, respectively). To ensure high water quality levels, water was replaced with a turnover rate of 150 L.day^{-1}.

Initially, four different plunge pool depths (D = 10, 20, 30, and 50 cm) and four waterfall heights (H = 5, 10, 15, and 25 cm; relative waterfall heights of 0.3, 0.5, 0.8, and 1.3 body lengths, respectively), providing 16 combinations (for more details on the selection of D and H, please see Amaral et al., 2016), were tested with a constant weir discharge (Q) of 50 L.s^{-1} (or a specific discharge [q] of 50 L.s^{-1} per unit width [50 L.s.m], because the weir is 1-m wide). Discharge was measured by a flow metre installed in the supply pipe of the flume. As for the different waterfall heights tested, they were settled by adding or removing modules from the weir (Figure 1c), and the plunge pool depths below the weir were controlled by a gate located at the downstream tank of the flume (Figure 2.1A). After these experiments, three additional discharges were tested (25, 75, and 100 L.s^{-1}) with the combination of waterfall height and plunge pool depth that previously showed the highest fish passage success. In all experiments, each combination tested had four replicates, carried out with schools of five fish per replica. Fish were randomly selected from the acclimation tanks and were used only once.

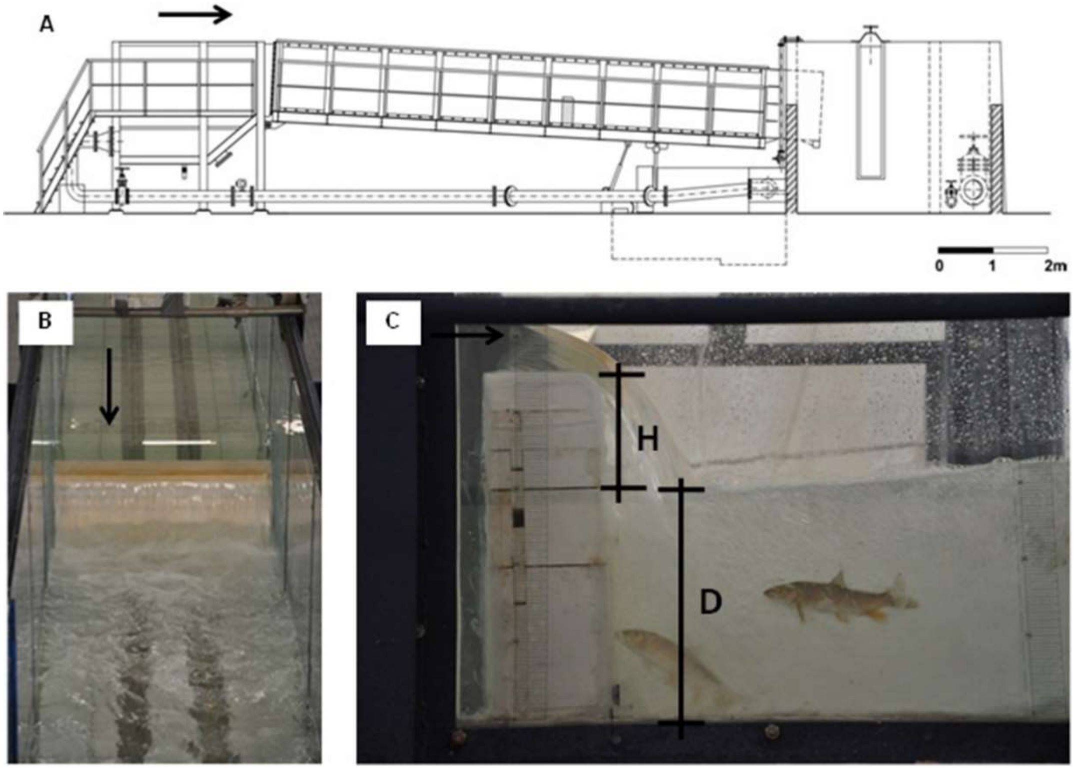

Fig. 2.1. Representation of (a) side view of the experimental channel on a slope of 3%; (b) experimental broad crested weir made of polyvinyl chloride modules used in the study, positioned in the flume 2.75 m upstream of the acclimation area; and (c) delimitation of the parameters plunge pool depth (D = distance from the bottom of the flume to the top of the water surface) and waterfall height (H = distance from the water surface to the top of the crest of the experimental weir). Arrows represent flow direction.

Prior to each experiment, fish were acclimatized to the flume conditions for 15 min. After this time, the upstream mesh panel of the acclimation area was removed, and fish were allowed to volitionally explore the flume for 60 min. Both upstream and downstream passage was allowed, so fish could negotiate the weir multiple times. Fish movements were monitored by direct observation and recorded (top view) by a video camera (GoPro HERO3). The number of times any fish actively tried to negotiate the weir (passage attempts; At), the number of successful upstream passages (N), and the type of successful passage behaviour (swimming through the nappe formed on the downstream face of the weir or jumping over the weir crest) were registered. For the passage attempts, the type of behaviour could not be reliably identified due to the presence, most of the time, of several fish below the weir, which hindered accurate visualization. In addition, on video recordings, turbulence derived from the energy dissipation of the plunging jet downstream the weir, also limited such assessment for some of the combinations (Amaral et al. 2016). Passage efficiency was calculated according to the equation presented in Amaral et al. (2016). Video recordings of all experiments were analysed to confirm the type of successful passage behaviour displayed by fish (Figure 2.2). At the end of each experiment, fish were measured for total length. All trials were performed during the natural reproductive migration of barbel, late spring and early summer (Santos et al. 2005), during the morning period (07–13 hr), to ensure that environmental conditions (light and temperature) where relatively constant throughout the experiments.

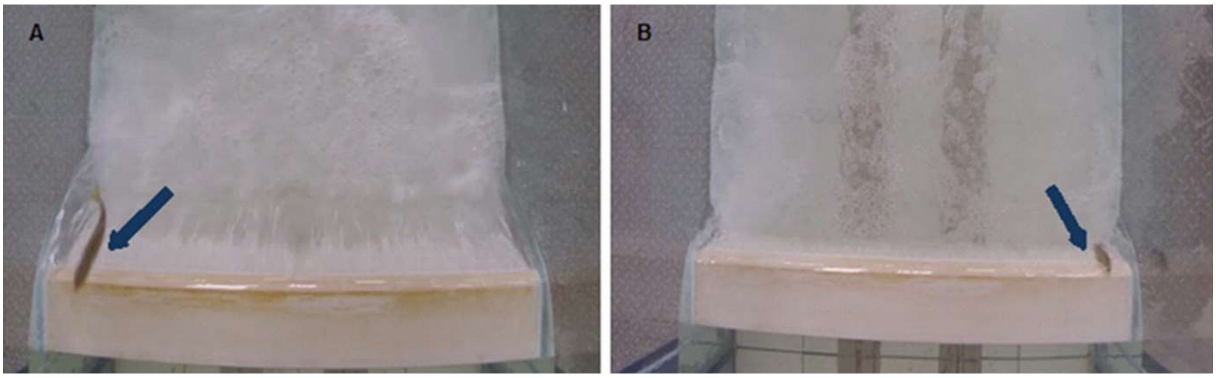

Fig. 2.2. Still frames from the video recordings (top view) showing the two observed passing behaviours of Iberian barbel: (a) by jumping and (b) by swimming through the water nappe formed in the downstream face of the weir.

2.3.3. Data analysis

To examine if the type of passage behaviour (response) was dependent on the 16 combinations tested (treatment), a Freeman-Halton test (a version of Fisher's Exact test, modified by Freeman and Halton 1951, normally applied to comparisons for tables greater than 2×2), followed by a post hoc test for pairwise comparisons, was performed using the package *rcompanion* (Mangiafico 2016) from the open-source software R (R Core Team, 2016). Additionally, the influence of D, H, and their interaction D × H on the type of passage behaviour of barbel, as well as on the switching of behaviour from swimming to jumping, was determined by performing a distance-based multivariate analysis of variance (MANOVA; PERMANOVA), using the Euclidean distance in the package PERMANOVA for PRIMER +v6.0 (Anderson et al. 2008). The same Freeman-Halton test was used to check the influence of discharge on the type of passage behaviour.

2.4. Results

Main results for each configuration tested, concerning passage attempts, total successful passages, and percentage of passage efficiency, are compiled in Table 2.1. As for the results on the type of passage behaviour, in the 16 combinations of D and H tested (Figure 2.3), 254 upstream attempts were successful, of which 207 (81.5%) were achieved by swimming through the water nappe formed in the downstream face of the experimental weir, and 47 (18.5%) were by jumping over the weir crest. Combination D20H10 (abbreviation for D = 20 and H = 10 cm) showed the highest number (45) of successful negotiations by swimming, representing 90% of the successes achieved under D20H10. The D30H10 and D50H05 combinations were followed with 26 (93%) and 24 (96%) successful outcomes, respectively. Nevertheless, in combinations D30H05 and D50H25, barbel was 100%

successful by swimming, although for these combinations a lower number of passage events were noted, 17 and 4, respectively.

In contrary, in combinations D10H25 and D30H25, barbel was 100% successful by jumping over the weir (with one and three successes, respectively), followed by combination D20H25 (18 jumps or 95% of successful outcomes). With a smaller percentage, combination D10H15 also stood out in this type of passage behaviour, with five successful jumps (28%).

Table 2.1. Main results for the combinations of plunge pool depths, waterfall heights, and discharges tested. D×H = configuration; Q = discharge (L.s^{-1}); n = number of fish tested; At = total number of attempts to pass the weir; N = total number of successful passages; %PE = percentage of passage efficiency (ratio of successful passages per number of attempts × 100).

D×H	Q	n	At	N	%PE
D10H05	50	20	65	10	15
D10H10	50	20	138	11	8
D10H15	50	20	90	18	20
D10H25	50	20	72	1	1
D20H05	50	20	183	9	5
D20H10	50	20	291	50	17
D20H15	50	20	248	24	10
D20H25	50	20	173	19	11
D30H05	50	20	328	17	5
D30H10	50	20	299	28	9
D30H15	50	20	204	9	4
D30H25	50	20	110	3	3
D50H05	50	20	196	25	13
D50H10	50	20	146	8	5
D50H15	50	20	171	18	11
D50H25	50	20	210	4	2
D20H10	25	20	280	14	5
D20H10	75	20	66	8	12
D20H10	100	20	12	1	8
Total	**-**	**380**	**3282**	**277**	**-**

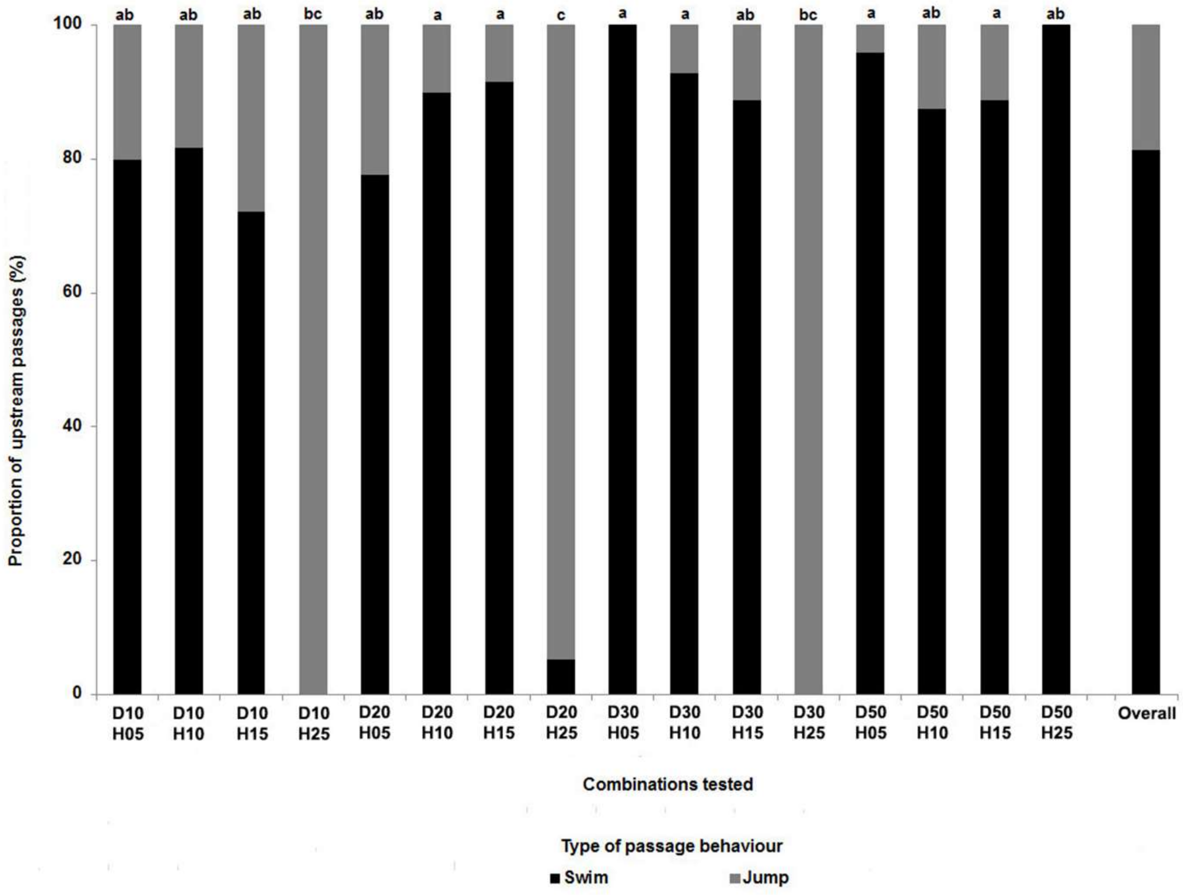

Fig. 2.3. Proportion (%) of upstream passages by swimming or jumping for the 16 combinations of plunge pool depths and waterfall heights tested (D×H), and results from the pairwise comparison after the main test Freeman–Halton. Combinations sharing a letter are not significantly different ($\alpha = 0.05$).

When analysing passage behaviour on configuration D20H10 during different weir discharges (Figure 2.4), it was found that, with the exception of the highest discharge ($Q = 100$ L.s^{-1}), when only a single passage swimming event occurred, in all other cases passage by jumping occurred, ranging from two (25%), for the discharge of 75 L.s^{-1}, to four (29%) and five successful outcomes (10%), for discharges 25 and 50 L.s^{-1}, respectively.

Results from the Freeman–Halton test showed that the type of passage behaviour (swim or jump) was highly dependent on the combination of plunge pool depth and waterfall height tested ($p < 0.0001$). Pairwise comparisons indicated that combinations D10H25, D20H25, and D30H25 had higher proportions of jumping negotiations and were significantly different ($p < 0.001$) from the other 13 combinations. Results of the PERMANOVA analysis showed significant effects of plunge pool depth (D; $F = 3.02$; $P = 0.01$), of waterfall height (H; $F = 8.43$; $P = 0.001$), and their interaction (D × H; $F = 3.52$; $P = 0.001$), on the type of passage behaviour adopted by fish to negotiate the weir. Pairwise comparisons (Table 2.2) performed for each factor showed that passage behaviour was significantly different for D10 versus D20, due to the high proportion of upstream passages by jumping over the weir registered in the combinations with D = 10 cm. As for waterfall height, H = 25 cm was significantly different from all other heights tested registering the highest number of successful outcomes by jumping. Regarding the discharge over the weir, in the range tested, there was no evidence that the type of passage behaviour was discharge-related (Freeman-Halton test, *P* > 0.05).

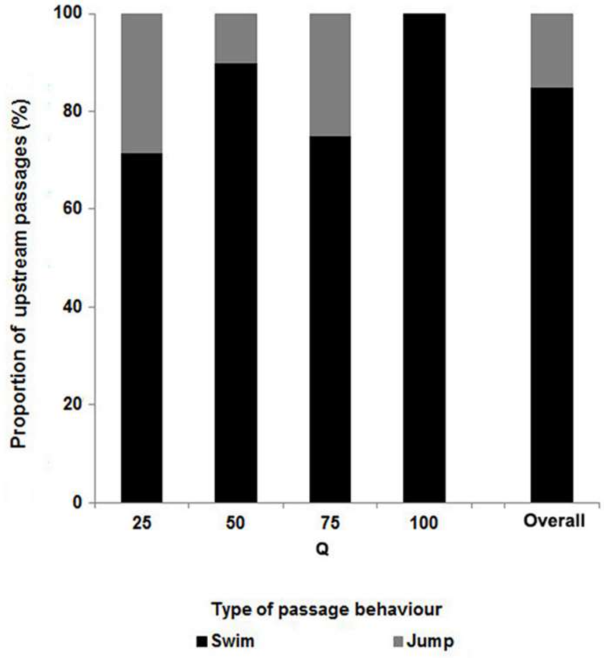

Fig. 2.4. Proportion (%) of upstream passages by swimming or jumping across increasing weir discharge (Q; $L.s^{-1}$) for configuration D20H10.

Table 2.2. Results of the pairwise comparisons, after the main test PERMANOVA, for factors that influenced the type of passage behaviour (swimming vs. jumping) of Iberian barbel: plunge pool depths (D) and waterfall height (H).

Factor	Pairwise comparisons	Results	
		t	*P*
D	**D10 vs. D20**	2.43	**0.004**
	D10 vs. D30	1.84	0.075
	D10 vs. D50	1.72	0.094
	D20 vs. D30	1.56	0.099
	D20 vs. D50	1.58	0.098
	D30 vs. D50	0.15	0.965
H	H05 vs. H10	1.79	0.092
	H05 vs. H15	0.40	0.779
	H05 vs. H25	3.94	**0.001**
	H10 vs. H15	1.41	0.157
	H10 vs. H25	4.30	**0.001**
	H15 vs. H25	3.37	**0.001**

2.5. Discussion

The experimental conditions tested in this study are a simplification of what fish may encounter in nature (Amaral et al. 2016). Nevertheless, laboratory studies are important (Lacey et al. 2012; Rice et al. 2010; Santos et al. 2014) to fill the knowledge gap about negotiation of small obstacles and passage behaviour of potamodromous cyprinid species. In laboratory experiments, target variables (such as plunge pool depth, waterfall height, and weir discharge tested in this study) can be easily manipulated, controlling possible confounding effects that could bias the results, and the observed responses will contribute to improve the understanding of events occurring in the wild (Kemp et al. 2006; Martin and Bateson 2007; Santos et al. 2014).

This study revealed the importance of plunge pool depth, waterfall height, and weir discharge, as well as their interaction, on the type of passage behaviour (swimming vs. jumping) adopted by Iberian barbel to negotiate small broad-crested weirs. The high number of attempts to pass the weir (Table 2.1), even in the most constraining combinations tested (e.g., D10H25 with Q = 50 L.s^{-1} or D20H10 with Q = 100 L.s^{-1}), as well as the number of successful outcomes demonstrated that Iberian barbel was motivated to move upstream and negotiate the weir. However, hydrodynamic conditions of each combination played an important role on the passage success (Amaral et al. 2016) and especially on the type of passage behaviour adopted by barbel to overcome the obstacle (this study).

Fish negotiated most configurations by swimming through the water nappe formed in the downstream face of the experimental weir. From 277 successful upstream passages (254 successes from the initial 16 configurations with Q = 50 L.s^{-1}, plus 23 successes from the three new discharges tested in D20H10 - 25, 75, and 100 L.s^{-1}), 224 (81%) were achieved by swimming, whereas only 53 (19%) were attained through jumps. This result is, in a way, in agreement with the expected passage behaviour for barbel, because potamodromous cyprinids are considered by some authors as a“non-jumping species (Baudoin et al. 2014; Doadrio et al. 2011). However, although jumping is not the passage behaviour most frequently used by these species to negotiate obstacles (Baudoin et al. 2014), most cyprinids when confronted with higher barriers to overcome, or high turbulence, are able to modify their individual passage behaviour increasing their attempts to pass by jumping (Baudoin et al. 2014; Morán-López and Tolosa 2017) and being successful in passing by this means, as found in this study.

Results demonstrate that the type of passage behaviour adopted by Iberian barbel to negotiate the experimental weir, by swimming or jumping, was highly dependent from the combinations of plunge pool depths and waterfall heights tested, and potentially on turbulence experienced downstream of the weir (see Amaral et al. 2016 for more details on hydrodynamic conditions). All configurations that featured the highest waterfall height (H = 25 cm) were mainly negotiated by jumping, except for the D50H25. Indeed, from the total of 53 upstream passages achieved by jumping, 22 (41.5%) were recorded at H = 25 cm (i.e., D10H25, D20H25, and D30H25). Furthermore, all (100%) successful passages at D10H25 and D30H25 (one and three successes, respectively) were achieved by jumping. Therefore, higher waterfall heights, which are directly associated with the formation of a standing wave (Powers and Orsborn 1985; Stuart 1962), higher energy dissipation of the plunging jet, more turbulence downstream of the obstacle, and more air entrainment (Baudoin et al. 2014; Pasternack et al. 2006; Wyrick and Pasternack 2008), are conditions that limit the upstream successful passages of fish (see Amaral et al. 2016) and proved to be an influencing factor in barbel switching passage behaviour from swimming to jumping. Moreover, as mentioned by Powers and Orsborn (1985) and Stuart (1962), associated with the standing wave formed downstream of the obstacle, velocities with an upward component normally occur that may also be influential in the switching of fish behaviour. In the case of D50H25, as the plunge pool downstream of the weir was deep enough to reduce the turbulence caused by the plunging jet (Baudoin et al. 2014; Towler et al. 2015) and to minimize the effect of the standing wave formed downstream of the weir (Powers and Orsborn 1985), all four upstream passages were achieved by swimming. As described by Lauritzen, Hertel, and Gordon (2005), the probability of fish, in the presence of deep plunge pools, to respond to the flows of waterfalls and to jump over the obstacle, decreases because fish tend to stay below the turbulence. In fact, even with a waterfall height of 25 cm, most attempts to pass the weir were by swimming through the water nappe formed in the downstream face of the weir. However, as that nappe was too vertical and equal to approximately 1.3 times the mean total length of the fish tested, the successes of passage were reduced and may have required great efforts by the fish. On the other hand, with the smallest plunge pool depth tested (D = 10 cm), the standing wave, turbulence, and air entrainment experienced immediately downstream of the weir (Baudoin et al. 2014; Powers and Orsborn 1985; Towler et al. 2015) may have influenced the number of attempts to negotiate the obstacle as well as the type of passage behaviour. Several times fish tended to approach the weir, in an attempt to negotiate it, but once reaching the zone of the plunging jet, they actively swam backward, probably due to the high turbulence and eddies, as it was reported by Elder and Coombs (2015), Liao (2007), Mirzaei (2017), and Stuart (1962). Therefore, passage attempts by jumping mostly initiated downstream the turbulence zone (avoiding the effect of the standing wave) were observed, indicating that the depth of the plunging pool was not a limiting factor, as mentioned by Ficke et al. (2011), Kondratieff and Myrick (2006), and Stuart (1962), and that barbel tried to individually restyle their passage behaviour to be successful (Mirzaei 2017). In fact, results from all four configurations with D = 10 cm (D10H05, D10H10, D10H15, and D10H25) represent approximately 19% of all successful jumps.

In terms of weir discharge, there was no evidence that passage behaviour was discharge-related for the range tested. Barbel overcame all the discharges tested mostly by swimming through the water nappe. Even in the trials with 100 L.s^{-1}, the only successful passage was by swimming, although it might be expected that, due to the higher turbulence and water velocity present in this configuration (see Amaral et al. 2016 for more details on hydrodynamic conditions), upstream passage would be by jumping over the crest of the weir. Instead, barbel managed to overcome the high turbulence and water velocities (TKE > 1 m^{2}.s^{-2} and V_{xz} > 1 m.s^{-1}; Amaral et al. 2016) and, taking advantage of the angular water nappe formed in the downstream face of the obstacle (Pasternack et al. 2006; Powers and Orsborn 1985), swam to negotiate the weir. This high swimming performance was also recorded in other studies (e.g., Branco et al. 2013; Morcillo and Castillo 2014; Romão et al. 2017; Santos et al. 2013; Sanz-Ronda et al. 2016; San-Ronda et al. 2015; Silva et al. 2012), demonstrating that this species can overcome conditions of water velocities and turbulence comparable to those surpassed by some salmonids of similar size (Katopodis and Gervais 2016; Mateus et al. 2008; Sanz-Ronda et al. 2016). Nevertheless, with Q = 100 $L.s^{-1}$, more than 50% of the observed attempts to pass the weir were by jumping. Still, those jumps were not successful because they were initiated too far from the weir (>30 cm downstream the weir), in order to avoid the zone of greater turbulence and high water velocities (Amaral et al. 2016), and were not long enough to overcome the obstacle. In addition, fish speeds and take-off angles of many of the jumps may not have been the most appropriate for success (Mirzaei 2017; Morán-López and Tolosa 2017; Powers and Orsborn 1985), resulting in short jumps. Another interesting result was the relevant percentage of successful jumps (29%) registered in the trials with 25 $L.s^{-1}$. It would be expected that, due to the small velocities (V_{xz} < 0.3 $m.s^{-1}$) and low turbulence (TKE < 0.07 $m^2.s^{-2}$) present in this configuration (more details in Amaral et al. 2016), all upstream attempts would be by swimming. However, unsuccessful passage attempts by swimming were observed because the water nappe that formed in the downstream face of the weir was too shallow (< 3 cm), limiting the free movements of barbel (Liao 2007; Powers and Orsborn 1985; Stuart 1962). So, as part of the "learning process" (Mirzaei 2017), barbel seized the opportunity offered by the low turbulence conditions immediately downstream of the weir and jumped to overcome the obstacle. Nevertheless, the small number of successful outcomes for this configuration, compared to the high number of attempts to pass the weir, revealed that low discharges may not be sufficiently efficient to allow fish to swim through the water nappe nor to attract fish to jump to negotiate the obstacle.

The outcomes of this study can be a great contribution, for both engineers and biologists, to identify potential migration obstacles and design more permeable barriers (Kondratieff and Myrick 2006; Ovidio et al. 2007), or even fishways less selective (Katopodis 2005; Katopodis and Gervais 2016), for this and other medium-sized potamodromous cyprinids. As identified in these experiments, waterfall height is one of the most important physical characteristics of broad-crested weirs that should be carefully considered when assessing the permeability of these obstacles to upstream fish movements. According to this assessment, the implementation of management measures should be considered on a case-by-case basis. This management may involve retrofitting the weir, to make it more suitable for fish passage (e.g., modifications of weir design; implementation of fish ramps), or even weir removal, when it is confirmed that it does not provide any service (such as environmental, economic, or social). Future studies on barriers to fish migration should focus on retrofitting actions, encompassing both upstream and downstream movements of fish.

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3. The effect of weir crest width and discharge on passage performance of a potamodromous cyprinid

Amaral, S.D.; Branco, P.; Romão, F.; Viseu, T.; Ferreira, M.T.; Pinheiro, A.N.; Santos, J.M. 2018. The effect of weir crest width and discharge on passage performance of a potamodromous cyprinid. Marine and Freshwater Research, 69. 1795–1804. Special Issue: Fish Passage 2018 & Hydropower Symposium. https://doi.org/10.1071/MF18075

3.1. Abstract

Contrary to the vast literature on dams, much less is known about the effects of small weirs on fish movements. This study aims to evaluate the upstream and downstream passage of the Iberian barbel (*Luciobarbus bocagei*), when facing a small broad-crested experimental weir with varying widths of the weir crest (W) and discharges (Q). Nine configurations (W × Q) were tested. Fish were released downstream of the weir and upstream and downstream passages were monitored. Hydrodynamics were characterised with a flow probe and a three-dimensional acoustic Doppler velocimeter (ADV). Fish negotiated all configurations, registering a total of 273 upstream passages and 192 downstream passages. The number of fish that approached, attempted and successfully ascended and descended the weir varied among configurations, emphasising the complex influence of factors on passage performance. Discharge was preponderant on both passages, proving that fish movements may be hampered by increasing discharges. However, the width of the weir crest only significantly influenced downstream passages, showing that strong velocity gradients experienced on narrower widths of the weir crest may discourage downstream movements. Results from the present study are expected to be useful to identify potential migration obstacles and may be applicable to other cyprinid species.

3.2. Introduction

River fragmentation, caused by the presence of instream obstacles, has been considered one of the most serious threats to the sustainability of fish populations (Aarts et al. 2004; Nilsson et al. 2005). During the past decades, the number of large dams and, particularly, small hydropower plants has greatly increased (Crook et al. 2015; Kelly-Richards et al. 2017; Couto and Olden 2018). Numerous studies have been conducted on the effects of large dams on ecosystems (Nilsson et al. 2005; Wilkes et al. 2018), to find solutions to overcome or minimise their adverse effects (e.g. implementation of fish-passage devices; Larinier and Marmulla 2004; Katopodis and Williams 2012). However, the effects on the river system of small man-made obstacles, such as weirs, which are far more numerous than are large dams (Nilsson et al. 2005; Ordeix et al. 2011), have received much less attention (Poulet 2007; Ordeix et al. 2011) because they are considered ‘a priori permeable’ to fish movements. Nevertheless, these small obstacles may successively alter the natural hydrodynamics of rivers, both upstream and downstream of the weirs, restricting longitudinal connectivity (O’Hanley 2011; Crook et al. 2015). Moreover, the permeability of such structures to fish movements depend on flow conditions (Harris et al. 2017), and fish swimming and jumping abilities, which are closely dependent on fish species and body size (Kemp and O'Hanley 2010; Newton et al. 2018).

The Portuguese rivers have more than 8000 small weirs (Ordeix et al. 2018) that are, in general, less than 5 m in height (Office National de L'eau et des Milieux Aquatiques 2010; Solà et al. 2011). As for the rest of the European countries, weirs were constructed between the 10th and 19th centuries (Birnie-Gauvin et al. 2017), for water storage and supply (especially for irrigation) and for small hydropower plants (Santos et al. 2006). Presently, some of these weirs have undergone maintenance and rehabilitation works, such as those involved in the requalification project 'Habitat restoration for diadromous fish in river Mondego, central Portugal', where five old weirs were retrofitted with nature-like fish ramps associated with modifications of the weir design (for more information, see http://www.rhpdm.uevora.pt/index.html, accessed 15 May 2018). However, a great number of weirs is obsolete or non-operational and these weirs represent a barrier for freshwater fauna. The effects of these weirs are usually site-specific (Kelly-Richards et al. 2017), varying according to the weir characteristics (e.g. the height of the weir and its slope) and hydrodynamic conditions (Baudoin et al. 2014) present both upstream and downstream of the obstacle (waterfall height to overcome, plunge pool depth downstream the weir, discharge, and, consequently, turbulence). So, as advocated by Birnie-Gauvin et al. (2017), an adaptive, step-by-step management should be implemented, to evaluate all services (ecological, social, economic and historical significance) associated with each barrier, and its overall impact on migratory success of the species present. It is, thus, necessary to know and understand all factors that may influence fish passage performance, both in the upstream and downstream directions.

Studies have been assessing the influence of key hydraulic parameters associated with small weirs, such as plunge-pool depths and waterfall heights, on upstream migration of fish (Stuart 1962; Ovidio and Philippart 2002; Kondratieff and Myrick 2006; Ficke et al. 2011; Amaral et al. 2016), especially for the most economically important species such as salmonids (Stuart 1962; Lauritzen et al. 2005: Ovidio et al. 2007; Kondratieff and Myrick 2006; Newton et al. 2018). Nevertheless, little empirical evidence exists for potamodromous cyprinid species (but see Benitez et al. 2015; Branco et al. 2017), particularly on the effects of small broad-crested weirs on upstream and downstream movements of these species. In Iberian rivers, small broad-crested weirs are the most usual design (Solà et al. 2011), being present in almost all watercourses. This type of weir, which normally spans the full width of the river channel, is generally constructed wittogh a vertical downstream face from reinforced concrete that may be extremely challenging for fish to negotiate it, especially for non-jumping species such as potamodromous cyprinids (Baudoin et al. 2014). The most usual passage behaviour of these species is to swim through the water nappe formed in the downstream face of small obstacles (Baudoin et al. 2014; Amaral et al. 2018). So, apart from hydraulic conditions such as plunge pool depth and waterfall height, which were previously tested in the study by Amaral et al. (2016), the physical characteristics of weirs, such as the weir profile and the geometry of the crest (e.g. the width of the crest), are also considered to play a preponderant role in the permeability of these obstacles to fish movements

(Baudoin et al. 2014). It is, thus, fundamental to consider such design characteristics and to develop further studies to assess passage performance of fish.

The present study aims to assess the upstream- and downstream-passage performance of a potamodromous cyprinid, the Iberian barbel (*Luciobarbus bocagei*), when encountering small broad-crested weirs, considering the isolated and interaction effects of width of the weir crest (W) and discharge (Q). The conditions tested are representative of those that fish are expected to overcome during their migratory movements (Branco et al. 2017). Iberian barbel was selected as the target species because it is considered representative of at least eight species of medium-sized benthic potamodromous cyprinids in Iberia and Western Europe (Santos et al. 2014). It was hypothesised that (1) successful upstream passage of barbel would decrease with an increasing crest width and increasing discharge, hampered by the increasing water velocity and turbulence present downstream and over the weir crest, as experienced in Amaral et al. (2016) and (2) downstream passage events would be more frequent with narrower widths of the weir crest in association with higher discharges, assuming that, when exposed to conditions of rapid water-velocity changes, fish may be more easily dragged downstream (Silva et al. 2016).

3.3. Materials and methods

3.3.1. Experimental facility

To study the effects of the width of the weir crest (W) and of discharge (Q) on upstream- and downstream-passage performance of Iberian barbel, an experimental broad-crested weir (total height = 0.30 m) made of polyvinyl chloride (PVC) modules was used. The experimental weir was installed in an indoor ecohydraulic channel present at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon. The channel (Figure 3.1A) consists of a rectangular steel frame (10.0 m long × 1.0 m wide × 1.2 m high), with a 3% slope, with glass-viewing panels on sidewalls that allow free observation of fish behaviour (further details of the facility are given in Amaral et al. 2016). The weir (Figure 3.1B,C) spanned the entire channel width and was fixed in the flume at 2.75 m upstream of the acclimation area, created in the downstream zone of the flume by two mesh panels 1 m apart. Immediately downstream of the weir, a 0.65-m-long zone was considered as the approach area and was continuously monitored. The different widths of the crest tested (W = 0.20, 0.40 and 0.80 m) were set up by adding modules (0.20 + 0.40 m) to the initial 0.20-m width weir (Figure 3.1C). Such dimensions were chosen a priori as representing common weir widths found in Iberian rivers (e.g. Solà et al. 2011; Branco et al. 2017). As for plunge-pool depth maintained downstream the experimental weir (D = 0.20 m) and waterfall height (H = 0.10 m), their selection was based on the results of a previous study by Amaral et al. (2016), who found it to be the best combination for maximising successful passage over the weir for the same species. Values of discharge tested (Q = 25, 50, and 100 $L.s^{-1}$) were measured with a magnetic flow meter installed in the supply pipe. Water quality in the flume was monitored (mean ± standard deviation (s.d.): temperature = 22 ± 18 ºC, pH = 8.2 ± 0.2, and conductivity = 161 ± 16 $\mu s.\ cm^{-1}$) after each experiment by using a multiparametric probe (HI 9812-5, HANNA instruments, Póvoa de Varzim, Portugal).

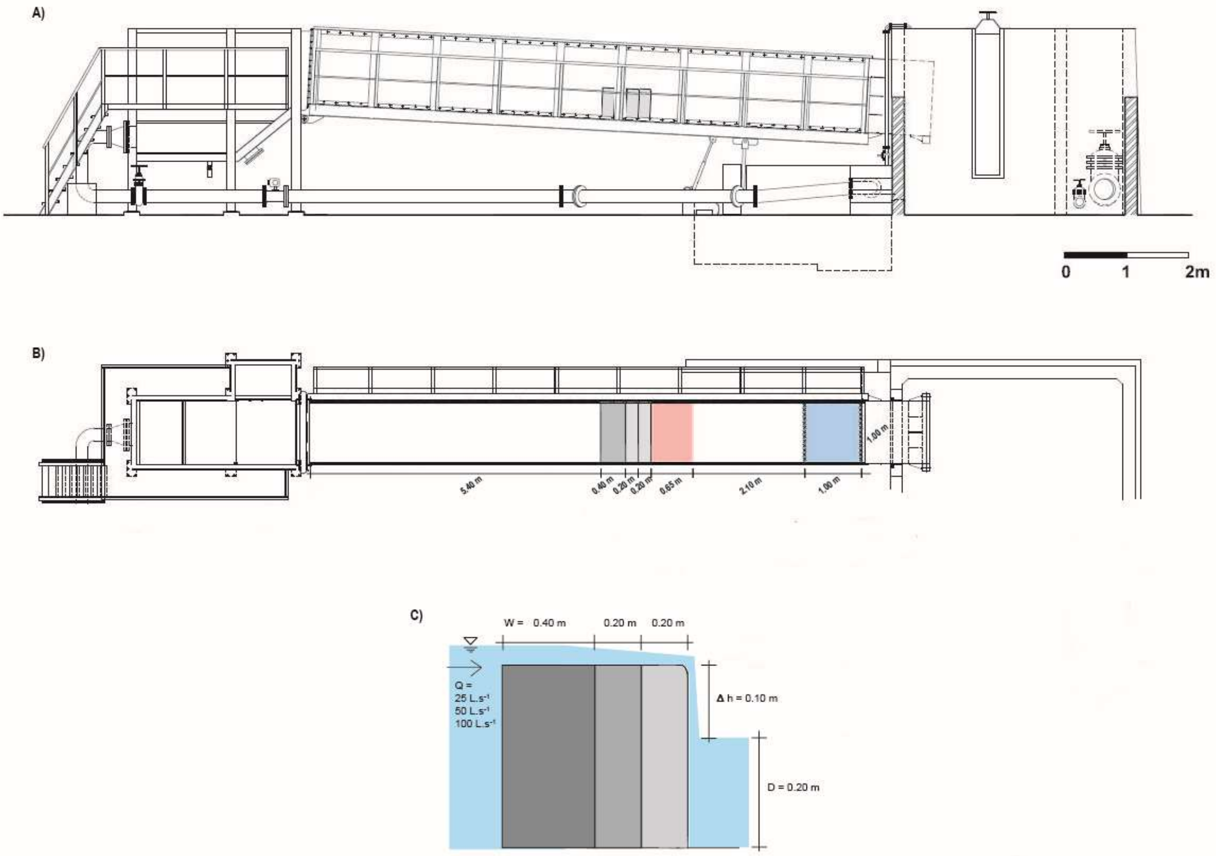

Fig. 3.1. Illustration of (a) side view of the experimental channel on a slope of 3%; (b) top view of the ecohydraulic channel presenting the location of the experimental weir (shaded in grey, and placed 2.75 m upstream of the acclimation area), the acclimation area (1-m^2 area shown between the two removable fine-mesh panels located downstream), and the approach area (0.65-m^2 area, immediately downstream the weir); and (c) experimental design representing the widths of the crest of the experimental weir (W = 0.20, 0.40, and 0.80 m) and discharges (Q = 25, 50, and 100 L.s^{-1}) tested, as well as plunge-pool depth downstream the weir (D = 0.20 m) and waterfall height to overcome (H = 0.10 m).

3.3.2. Fish collection

In total, 180 adult Iberian barbel (mean total length (TL) ± s.d. = 185 ± 29 mm) were used in the experimental work. Fish were previously captured in the Lizandro River, a small Atlantic coastal river. Site selection was based on habitat representativeness, i.e. taking into account the presence of well-defined run-riffle sections and lack of severe human impact. Sampling was performed by wadable electrofishing (IG-200, Hans Grassl, Schönau am Königssee, Germany) according to the protocol adopted by the European Committee for Standardization (2003).

Three electrofishing episodes were performed (one episode per week), collecting 60 fish per episode. Only adult fish were selected for the laboratory experiments to avoid bias in swimming performance. A fish-transport box (190-L, Hans Grassl, Germany) with external aeration was used to transport the fish to the laboratory facilities at LNEC, where they were maintained in filtered and aerated acclimation tanks (700-L tanks; High Performance Canister Filter FX5, Fluval, Québec, QC, Canada) for a maximum period of 6 days, of which at least 48 h were of acclimation to holding conditions. During that period, fish were fed with Tetra Pond sticks up to 24–48 h before the experiments. Water quality in the acclimation tanks was also monitored (temperature = 22 ± 18C, pH = 7.5 ± 0.2, and conductivity = 168 ± 16 μs.cm^{-1}), and high-quality levels (i.e. active fish, no mortality) were maintained by the mechanical and biological filtration system, with a turnover rate of 2300 L.h^{-1}.

3.3.3. Experimental setup

Experiments were conducted in agreement with national and international guidelines to maintain the welfare of the tested animals and minimise stress (J. M. Santos holds FELASA Level C certification (see www.felasa.eu, accessed 15 May 2018) to direct animal experiments).

Nine configurations (W× Q), considering the factorial design of W (3 levels = 0.20, 0.40 and 0.80 m) and Q (3 levels = 25, 50 and 100 L.s^{-1}), were tested. Each configuration had four replicates, performed with schools of five fish (n = 20 fish) that were not individualised. Fish were randomly selected from the acclimation tanks and were used only once. Each replicate started with an acclimation period of 15min, for fish to adapt to the flume conditions. After that time, the upstream mesh panel of the acclimation area was removed, and fish were able to explore the channel for 60 min. Because upstream and downstream passages were allowed, fish could negotiate the weir multiple times. Fish movements were recorded by a video camera (GoPro HERO3, GoPro Inc., San Mateo, CA, USA) and monitored by direct observations. The number of times fish entered the approach area (Ap; considered when the fish moves the whole body into the approach area, located 0.65 m downstream of the weir), the number of times fish actively tried to upstream negotiate the weir (At; counted when fish initiated the movement of swimming through the water nappe formed in the downstream face of the experimental weir, or when it tried to jump, to overcome the weir), and the number of successful upstream (UP; counted when the whole-body length of fish completely passed the weir crest and moved upstream) and downstream passages (DP; when fish completely passed the weir to downstream) were registered. Regarding the downstream movements, no downstream passages were observed in which the fish had been dragged shortly after making their passage to upstream. At the end of each experiment, fish were measured for TL.

3.3.4. Characterisation of hydrodynamics

A downward-looking three-dimensional acoustic doppler velocimeter (Vectrino ADV, Nortek AS, Oslo, Norway) was used to characterise the hydrodynamic conditions downstream of the weir. The three components of flow velocity (x, y, z) were measured in 25 sampling points implemented in one vertical plane at the centre of the flume, assuming flow symmetry across its width (Figure 3.2). The spacing of sampling points was established according to the expected velocity-field variation and considering the limitations of the ADV equipment (the probe must be completely immersed during data acquisition, and a minimum distance of 5 cm should be preserved from the bottom of the flume and near the obstacle). Sampling points immediately downstream of the weir were discarded because of problems of high turbulence and aeration, conditions that limit the acquisition of quality data by the ADV

(Quaresma et al. 2017). Velocity data were acquired at a 25-Hz sampling rate, during 180 s. During the measurements with the ADV, a signal-to-noise ratio (SNR) between 15 and 25 dB and correlations (COR) above 60% were always guaranteed. Regarding the characterisation of the flow nappe over the crest of the experimental weir, because water depth was not enough for the ADV equipment, a flow probe (Model FP101, Global Water Instrumentation, Inc., College Station, TX, USA) was used to measure water velocity. The water depth over the weir crest in each configuration was also registered.

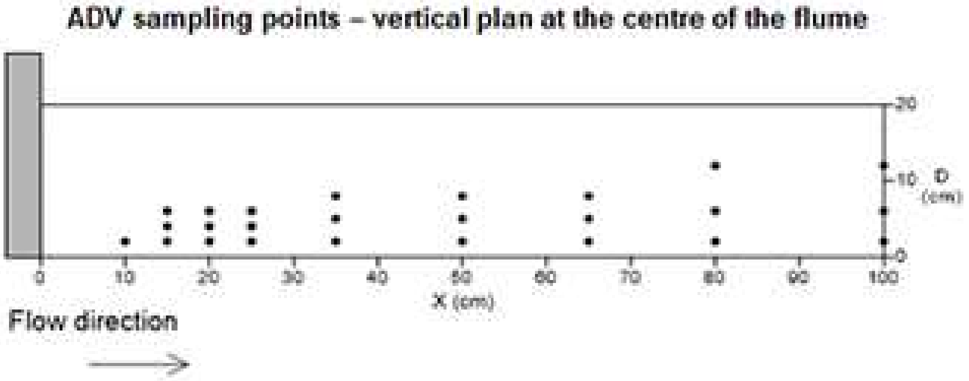

Fig. 3.2. Distribution of the 25 sampling points along the centre of the flume where the velocity measurements were performed with the three-dimensional acoustic doppler velocimeter (Vectrino ADV, Nortek AS, Oslo, Norway).

3.3.5. Data analysis

To assess upstream passage past the experimental weir for the configurations tested (W × Q), the percentage of attraction efficiency (AE) and passage efficiency (PE) were calculated from Equations 1 and 2, as in Amaral et al. (2016), as follows:

$$\text{AE \%} = 100 \times \frac{\text{number of times fish attempted to negotiate the weir}}{\text{number of times fish entered the approach area}} \qquad (1)$$

$$\text{PE \%} = 100 \times \frac{\text{number of successful passages}}{\text{number of times fish attempted to negotiate the weir}} \qquad (2)$$

To analyse the influence of W and Q, as well as their interaction, on the number of successful upstream passages of Iberian barbel, a PERMANOVA test applying the Euclidean distance, was performed using the package PERMANOVA for PRIMER+ (ver. 6.0, PRIMER-E, Plymouth, UK; Anderson et al. 2008). PERMANOVA is a non-parametric method based on permutation tests that directly partitions the variation in a distance matrix according to Euclidean distances or non-Euclidean-embeddable dissimilarity measures (Anderson 2001, 2017). It computes a distance-based multivariate test analogue to the Fisher's F-ratio for each factor and calculates P-values using appropriate permutation methods, requiring no specific assumption regarding the number of variables or their individual distributions or correlations (Anderson 2001, 2017; Anderson et al. 2008). Euclidean metric was applied to compute the distance matrix because of the presence, and relevance, of zeros in the analysed data (Anderson et al. 2008). Regarding downstream passages, given that their number is dependent on the number of successful upstream passages recorded in each configuration, proportions were calculated, to standardise the values, considering the ratio between the number of downstream passages and the number of upstream passages registered. A proportion test was conducted, using the stats package from the open-source software R (R Foundation for Statistical Computing, Vienna, Austria, see http://www.R-project.org/, accessed 15 January 2018), to verify whether there were differences in the proportions of downstream passage for the configurations tested. Likewise, to test the effect of W and Q, and their interaction, on the number of downstream passages of Iberian barbel, a PERMANOVA test was performed using the Euclidean distance as before.

Data on instantaneous velocity (V_i) were filtered with WinADV freeware software (US Department of the Interior, Bureau of Reclamation Water Resources Research Laboratory, Denver, CO, USA; Wahl 2001), using the Goring and Nikora (2002) phase-space threshold despiking method, as modified by Wahl (2003). To analyse velocity fluctuations and turbulence gradients along a vertical plane, the resultant V_{xz} and turbulent kinetic energy (TKE) were calculated (Equations 3 and 4, respectively) and represented graphically by contour maps, to illustrate the hydrodynamic conditions within the approach area (e.g. areas of high velocity and turbulence gradients) that might have influenced fish movements. In addition, differences in flow velocities and turbulence were further analysed using a nonparametric Friedman test, followed by a Nemenyi post hoc test applying the R package PMCMR (ver. 1.1, T. Pohlert, see http:// CRAN.R-project.org/package=PMCMR, accessed 15 January 2018).

$$V_{xz} = (V_x^2 + V_z^2)^{1/2} \qquad (3)$$

$$\text{TKE} = {}^{1}\!/_{2}\ \left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) \qquad (4)$$

3.4. Results

Overall, fish negotiated all configurations tested, registering a total of 273 upstream and 192 downstream passages. Nevertheless, the number of times fish approached the weir, the number of attempts to pass, and the successful upstream and downstream passages varied among configurations.

For the upstream passages (Table 3.1), an average of 604 approach movements (maximum: 1440 approaches, in W20Q25; minimum: 26, in W20Q100) and of 207 attempts to negotiate the experimental weir (maximum: 434 attempts, in W40Q25; minimum: 12, in W20Q100) were registered. The highest number of upstream passages was recorded in configuration W40Q25, with 52 successes, followed by configurations W20Q50 and W80Q50, with 50 and 48 upstream negotiations respectively. The poorest performance was registered for configuration W20Q100, with 26 approaches, 12 attempts to pass the weir, and only one successful passage.

Regarding downstream passages (Table 3.1), the highest number was recorded in configuration W40Q25, with 41 passages. However, in terms of the proportion of the number of downstream per number of upstream passages, the highest ratio was registered in W40Q50, with 80.8% (with 21 downstream passages from a total of 26), followed by W40Q25 with 78.8% (41 downstream passages from a total of 52 upstream successes). No downstream passages were recorded in configuration W20Q100. All fish descended the weir tail first with a passive behaviour (100%), not swimming but maintaining stability.

Table 3.1. Upstream and downstream movements of Iberian barbel past the experimental broad-crested weir Conf, configuration abbreviation considering the width of the crest of the experimental weir (W, cm); Q, the discharge (L.s^{-1}); Ap, total number of approaches; At, total number of attempts to pass the weir; UP, total number of successful upstream passages; %AE, percentage of attraction efficiency (ratio of the number of attempts per number of approaches × 100); %PE, percentage of passage efficiency (ratio of successful upstream passages per number of attempts × 100); DP, downstream passages; %DP, proportion of downstream passages (ratio of downstream passages per upstream successes × 100)

		Upstream Passage				**Downstream Passage**	
Conf	**Ap**	**At**	**UP**	**AE %**	**PE %**	**DP**	**DP %**
W20Q25	1440	280	14	19	5	5	35.7
W20Q50	548	291	50	53	17	38	76.0
W20Q100	26	12	1	46	8	0	0.0
W40Q25	1192	434	52	36	12	41	78.8
W40Q50	585	218	26	37	12	21	80.8
W40Q100	166	110	25	66	23	16	64.0
W80Q25	894	287	44	32	15	32	72.7
W80Q50	442	175	48	40	27	34	70.8
W80Q100	141	58	13	41	22	5	38.5

Results of the PERMANOVA analysis indicated a significant effect of Q (*F* = 5.48; *P* = 0.008) on the number of upstream-passage events. Pairwise comparison performed for this factor (Table 3.2) showed that the number of successful upstream passages was significantly different, and lower, for Q = 100 L.s^{-1}, than to the other tested discharges (Q25 vs. Q100: *t* = 2.70; *P* = 0.009; and Q50 vs. Q100: *t* = 3.66; P ≤ 0.01). As for W (*F* = 1.34; *P* = 0.264), and the interaction W × Q (*F* = 2.18; *P* = 0.09), there was no evidence of influence on upstream passage of fish. Concerning downstream-passage events, results of the proportion test (*Z* = 21.28; 8 *d.f.*; *P* = 0.006) showed that the proportion of downstream passages was significantly different for each configuration tested. Results of the PERMANOVA test showed significant effects of W (*F* = 5.16; *P* = 0.016), Q (*F* = 6.66; *P* = 0.009), and the interaction W × Q (*F* = 2.96; *P* = 0.03) on the proportion of downstream passage of fish. Pairwise comparisons performed for both factors W and Q (Table 3.2) showed that the proportion of downstream passages was significantly different, and lower, for W = 20 cm, than to the other tested crest widths (W20 vs. W40: *t* = 3.54; *P* ≤ 0.01; and W20 vs. W80: *t* = 2.21; *P* ≤ 0.050), and that Q = 50

$L.s^{-1}$ was significantly different from Q = 100 $L.s^{-1}$ (Q50 vs. Q100: *t* = 3.81; $P \leq 0.01$), registering the highest proportion of downstream movements.

Table 3.2. Results of the pairwise comparisons, after the main test PERMANOVA, on the upstream- and downstream-passage movements of Iberian barbel past the experimental broad crested weir, according to the width of the experimental weir (W) and discharge (Q) Values in bold highlight significant differences. α = 0.05.

Movement direction	Factor	Pairwise comparisons	Results	
			t	***P***
Upstream	**Q**	Q25 vs. Q50	0.43	0.687
		Q25 vs. Q100	**2.70**	**0.009**
		Q50 vs. Q100	**3.66**	**<0.01**
Downstream	**W**	**W20 vs. W40**	**3.54**	**<0.01**
		W20 vs. W80	**2.21**	**0.050**
		W40 vs. W80	0.70	0.47
	Q	Q25 vs. Q50	1.77	0.094
		Q25 vs. Q100	1.81	0.099
		Q50 vs. Q100	**3.81**	**<0.01**

3.4.1. Hydrodynamics

Contour maps, showing the variation of water velocity (resultant V_{xz}; Figure 3.3) and TKE (Figure 3.4) for the tested configurations, showed that both hydraulic parameters increased with discharge. This increase was particularly expressive for Q =100 $L.s^{-1}$, where values of V_{xz} and TKE above 1 $m.s^{-1}$ and 1.4$m^2.s^{-2}$, recorded close to the toe of the weir, were registered. For Q = 25 $L.s^{-1}$, values of V_{xz} and TKE registered close to the toe of the weir were considerably lower, with 0.5 $m.s^{-1}$and 0.26 $m^2.s^{-2}$. Measurements with the flow probe along the width of the weir crest, from the upstream to the downstream portion of the crest, showed water-velocity values ranging from 0.6 to 0.9 $m.s^{-1}$, for configurations with Q = 25 $L.s^{-1}$, 0.9–1.2 $m.s^{-1}$, for Q = 50 $L.s^{-1}$, and 1.1–1.8 $m.s^{-1}$, for Q = 100 $L.s^{-1}$. Water depth over the weir crest varied from ≈ 0.03, ≈ 0.05 and ≈ 0.07 m, when Q = 25, 50 and 100 $L.s^{-1}$ respectively.

Statistical comparison of water velocity, V*xy*, (*Fr* = 36.84; 8 *d.f.*; *P* < 0.01) and TKE (*Fr* = 160.15; 8 *d.f.*; *P* < 0.01) showed significant differences among the different configurations. Results of pairwise comparisons revealed that the three configurations with Q = 100 $L.s^{-1}$ were significantly (*P* < 0.05) different from the remaining ones, presenting higher values of water velocity and especially of TKE close to the toe of the experimental weir.

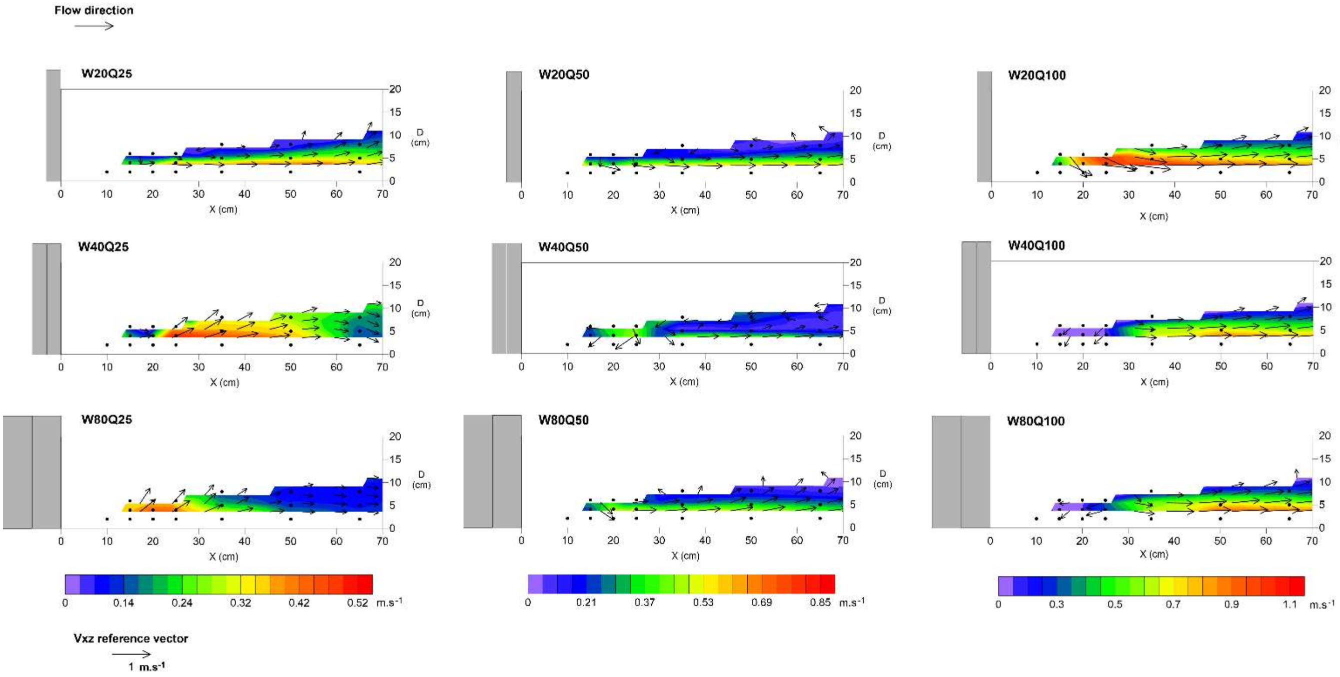

Fig. 3.3. Representation of water velocity (V_{xz}; m.s^{-1}) magnitude and direction for combinations of the width of the experimental weir and discharge (W × Q) tested. X is the distance from the weir (cm) and D is the water depth (cm). Points represent the measuring mesh. Measurements were taken with an acoustic doppler velocimeter (Vectrino ADV, Nortek AS, Oslo, Norway).

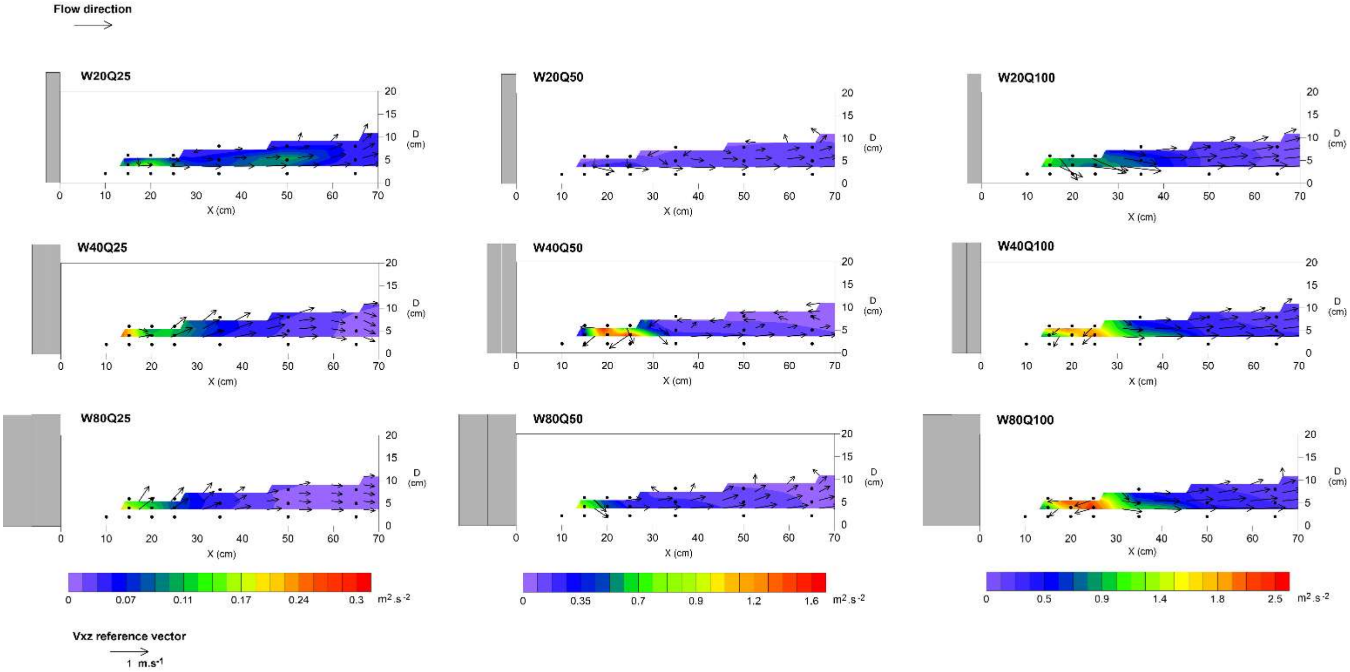

Fig. 3.4. Representation of turbulent kinetic energy (TKE; m^2.s^{-2}) intensities and velocity vectors (V_{xz}) for combinations of the width of the experimental weir and discharge (W × Q) tested. X is the distance from the weir (cm) and D is the water depth (cm). Points represent the measuring mesh. Measurements were taken with an acoustic doppler velocimeter (Vectrino ADV, Nortek AS, Oslo, Norway).

3.5. Discussion

The present study focussed on the effect of the crest width of a small broad-crested weir, and of discharge, on passage performance of a potamodromous cyprinid, the Iberian barbel. The fact that experiments were conducted under laboratory conditions, in an indoor ecohydraulic channel, allowed the detailed observation of fish behaviour (e.g. fish approaching the weir, attempts to pass, successful passages) as well as the control and analysis of all the physical and hydraulic factors considered preponderant in the successful passage of fish species. According to some authors (Kemp et al. 2006; Alexandre et al. 2013; Santos et al. 2014; Amaral et al. 2016), although laboratory studies often simplify the conditions that species encounter in nature, such as, for example, temperature, substrate roughness, weir-geometry irregularities, channel cover and complexity, they do provide the opportunity to control for confounding variables, manipulate target factors and observe responses, improving the understanding of events occurring in the wild. Furthermore, fish used in these experiments were chosen within the range of 15–25 cm TL, which is representative of the typical size class of natural adult fish that are the most active in upstream migration, and so, different behaviours and abilities may be expected in experiments, and in the field, with other size classes.

In this study, by keeping variables such as plunge-pool depth and waterfall height constant, which were previously tested in the study by Amaral et al. (2016), it was possible to isolate and determine the influence of the width of the weir crest and discharge, as well as their interaction, on passage performance of Iberian barbel, considering both upstream and downstream passage responses. The number of approaches to the weir, attempts to pass, and successful negotiations recorded throughout all experiments confirmed that fish were motivated to move upstream. However, results varied according to combinations of W and Q, implying that hydrodynamic conditions were more suitable for fish to negotiate the weir in some of the configurations tested, as also shown in Amaral et al. (2016).

As has been reported in other studies (Silva et al. 2012; Santos et al. 2013, 2014; Amaral et al. 2016), Q proved to be an important factor, influencing both the upstream- and downstream- passage performance of Iberian barbel. In fact, Q is determinant and can be regarded as a proxy for several hydraulic variables (e.g. turbulence) downstream of vertical face weirs, influencing the swimming costs and habitat selection of fish (Wilkes et al. 2017), and, thus, structuring upstream and downstream fish assemblages (Baumgartner et al. 2014).

Upstream passages, as well as fish approaches and attempts to pass the weir, mainly decreased with an increasing discharge, especially for the configuration with the narrowest width of the crest, W20Q100. Of all the movements registered, configurations with Q = 100 $L.s^{-1}$ achieved only 14% of all the upstream passages, and 9 and 6% of total attempts and approaches respectively. Under such discharge, high values of water velocity and turbulence, above $1 m.s^{-1}$ and $1.4 m^2.s^{-2}$, were observed downstream of the experimental weir, which may have limited the ability of fish to approach the obstacle (Pavlov et al. 2000; Liao 2007; Elder and Coombs 2015) and successfully negotiate it. In contrast, configurations with the lowest discharge tested, Q = 25 $L.s^{-1}$, which showed lower water velocity and turbulence close to the experimental weir ($0.5 m.s^{-1}$ and $0.26 m^2.s^{-2}$), achieved a high number of fish approaches (65% of total approaches registered) and attempts to pass the weir (54% of all the attempts observed), although they ranked the lowest in terms of AE and PE. These results agree with the concept of the “fish-passage paradox” mentioned by Goerig and Castro-Santos (2017) regarding the influence of discharge in the negotiation of obstacles; in the present study, discharge had a positive influence on the attraction of fish to the weir but, at the same time, it might have been a limiting factor for the successful passage. Under such low discharge (Q = 25 L.s^{-1}), the less turbulent plunging jet, associated with a shallow water nappe (≈ 0.03 m) over the weir and a nappe profile formed on the downstream face of the obstacle to vertical, might have represented less favourable conditions (Pasternack et al. 2006; Baudoin et al. 2014; Towler et al. 2015) for an effective upstream fish passage past the experimental weir (Powers and Orsborn 1985; Pavlov et al. 2000; Baudoin et al. 2014). As for Q = 50 L.s^{-1}, considering the overall number of upstream passages, this was the most successful discharge, with 46% of all the upstream successful passages. From all the combinations tested, configuration W80Q50 was the best in terms of PE, presenting 27% of efficiency for upstream passage, and ranked third in the number of successful negotiations across the experimental weir. Similar results were also reported by Amaral et al. (2016), on testing the influence of discharge on upstream-passage performance of Iberian barbel.

Regarding downstream passage, Q = 50 L.s^{-1} was also the discharge with more downstream passages, both in number and proportion. This discharge presented a 75% ratio of the number of downstream passages per successful upstream negotiations (considering the results of all three configurations with Q = 50 L.s^{-1}), followed by Q = 25 L.s^{-1}, with 71% of the total number of downstream movements per upstream passages. In contrast, Q = 100 L.s^{-1} was the discharge tested with the lowest number and proportion of downstream movements (54%), a fact that may be explained by the natural behaviour of fish to avoid areas with high water velocity and turbulence (Elder and Coombs 2015; Silva et al. 2016), such as those that should have formed with this high discharge tested. So, with Q = 100 L.s^{-1}, fish tended to swim upstream, away from the influence of the weir, and remained there possibly trying to find areas in the flume with lower water velocity.

Concerning the influence of W on the passage performance of Iberian barbel, contrarily to what was hypothesised, increasing widths did not restrict the successful upstream passages across the weir. Overall, configurations with W = 0.80 m registered 38% of all successful upstream passages (a total of 105 upstream passages), followed by W = 0.40 m with also 38% (103 upstream passages), and W = 0.20m registered the lowest value with only 24% of total upstream passages (65 upstream passages). Therefore, Iberian barbel managed to swim along all tested widths, and was able to withstand unfavourable hydraulic conditions, such as a shallow water depth (≈ 0.03 m, for Q =25 L.s^{-1}) or high water velocities (e.g. from 1.1 to 1.8 m.s^{-1}, for Q = 100 L.s^{-1}) above the weir crest. Although some authors refer to potamodromous cyprinids, such as Iberian barbel, as being weaker swimmers than are salmonids (Alexandre et al. 2013; Katopodis and Gervais 2016), the high swimming performance recorded in the present work has also been reported in other studies (Silva et al. 2012; Branco et al. 2013; Santos et al. 2013; Sanz-Ronda et al. 2015, 2016; Romão et al. 2017), revealing that this species can overcome conditions of water velocities and turbulence comparable to those surpassed by some salmonids of similar size (Mateus et al. 2008; Katopodis and Gervais 2016; Sanz-Ronda et al. 2016). Moreover, the demonstrated ability of Iberian barbel to swim along shallow waters, with depths less than the 10 cm recommended in previous studies (Solà et al. 2011; Baudoin et al. 2014), suggests that more experiments should be conducted to better understand the effective negotiation of these species over these obstacles.

As for the effect of W on results of downstream passages, it significantly influenced the downstream movements of fish. Contrary to what was expected, configurations with the narrowest width, i.e. W = 0.20 m, stood out from the other widths, registering the lowest values of downstream passages (43 passages), and also the lowest proportion of downstream passages per number of upstream passages (66%). This was especially evident in the configuration W20Q100, in which no downstream passage was recorded. Although we could not determine three velocity components on the top of the weir because of ADV limitations (see Materials and methods), it is possible that velocity gradients resulting from the tested discharges, observed on such short space, were too strong to encourage downstream movements (Williams et al. 2012). Further research will be required to address this issue.

In conclusion, the present study showed the importance of width and discharge, as drivers of upstream and downstream movements of a potamodromous cyprinid species past an experimental broad-crested weir. Some results were different from those previously expected, such as the high number of upstream passages recorded for W = 0.80 m and for Q = 50 L.s^{-1}, or the low number of downstream passages registered with W = 0.20m and Q = 100 L.s^{-1}. Thus, these results emphasise the complexity and the importance of the crest width and discharge on fish negotiation of small broad-crested weirs.

The outcomes of this work, together with previous studies from Amaral et al. (2016, 2018) on the influence of key factors such as plunge-pool depth and waterfall height on the passage performance of Iberian barbel, may be used as indicator values for assessing the permeability of small barriers and, thus, identifying potential migration obstacles for potamodromous cyprinids. Likewise, these values can also establish important thresholds that may help define design criteria for the requalification of small barriers (Ovidio and Philippart 2002; Kitchen et al. 2016; Birnie-Gauvin et al. 2017), improving fish movements, population management and habitat connectivity (Meixler et al. 2009; Lintermans 2013). Furthermore, the implications of this research may be applicable to other cyprinid species with similar life-history requirements that oblige passage through instream hydraulic structures.

It is clear that the development of a central, geospatial database containing physical and hydraulic characteristics of barriers, surrounding habitat conditions and long-term flow data (Kemp and O'Hanley 2010) is essential to aid scientists and managers in implementing proper mitigation programs to facilitate fish passage, either through their removal or retrofitting. Additionally, further studies are required, especially for different weir-crest shapes and widths, under distinct flow magnitudes, for the development of practical relationships in the prediction of up and down weir negotiation.

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IV. Low–Head Ramped Weirs

1. Passage Performance of Potamodromous Cyprinids over an Experimental Low-Head Ramped Weir: The Effect of Ramp Length and Slope

Amaral, S.D.; Branco, P.; Katopodis, C.; Ferreira, M.T.; Pinheiro, A.N.; Santos, J.M. 2019. Passage Performance of Potamodromous Cyprinids over an Experimental Low-Head Ramped Weir: The Effect of Ramp Length and Slope. Sustainability, 11. 1456. https://doi.org/10.3390/su11051456

1.1. Abstract

Low-head ramped weirs are a common instream obstacle to fish movements. Fish passability of these structures, where water passes over but does not generate a waterfall, is primarily related to ramp length and slope, but their relative contribution has seldom been considered. This study aims to assess the passage performance of a potamodromous cyprinid, the Iberian barbel (*Luciobarbus bocagei*), negotiating an experimental ramped weir with varying ramp length (L) and slope (S). Four configurations were tested, with a constant discharge of 110 L.s^{-1}. Results suggest that both factors influenced passage performance of fish. Attraction efficiency (AE) increased with increasing L and S, whereas the number of successes (N) and passage efficiency (PE) decreased upon increasing L. For S, it was found that both N and PE peaked at the intermediate level (20%). These results suggest that configurations with the lowest slopes may not necessarily be the best option because they may be less attractive for the fish and their demand for space is higher. Higher slopes (but not excessive) could be more attractive to fish, less space-demanding, and therefore, more cost-effective. Future studies should investigate how discharge and boulder placement influence fish passage across ramped weirs, to improve habitat connectivity.

1.2. Introduction

River fragmentation by small engineered structures, far more numerous than dams, has led to severe declines or local extinctions of many fish populations by blocking upstream movements for reproduction, feeding, and refuge needs (Aarts et al. 2003; Nilsson et al. 2005; King et al. 2017). By identifying the importance of aquatic connectivity for good ecological quality in rivers, the European Water Framework Directive (WFD) emphasized the need to re-establish free movements for all fish species and size classes, regulating that member states should assess all instream obstacles, even small weirs, and minimize their barrier effect (European Commission 2000; Reyjo et al. 2014; Barry et al. 2018). Since then, a few studies on small obstacles (considering assessment protocols, e.g., Ovidio et al. 2007; Solà et al. 2011; Schmutz and Mielach 2013, or field assessments, e.g., Ovidio and Philippart 2002; Weibel and Peter 2013; Ordeix 2017) and projects, such as the European project

AMBER and other operational programs like the EU LIFE programs, have been developed, aiming to enhance the knowledge on permeability of small obstacles and fish passage, recommend strategies for action, and rehabilitate river habitats (King et al. 2017; Birnie-Gauvin et al. 2018; Ordeix et al. 2018).

Portuguese rivers have more than 8000 small weirs (Ordeix et al. 2018) that are, in general, less than 5 m in height. Along with small broad-crested weirs (designed with a vertical downstream face; Amaral et al. 2016), low-head ramped weirs, with inclined faces that fish may be able to overcome by swimming, are the most usual design (Solà et al. 2011; Branco et al. 2017). In fact, some old broad-crested weirs that, after assessment, could not be removed have undergone rehabilitation works to include ramps in their designs, in order to enhance fish passability (e.g., FAO/DVWK 2002). However, the effectiveness and efficiency of these structures remains poorly understood, particularly for potamodromous cyprinids, which are an important component of Mediterranean European fish assemblages (Ferreira et al. 2007).

In low-head ramped weirs, water passes over the ramp and does not generate a waterfall (Solà et al. 2011; Baudoin et al. 2014). The permeability of such structures to fish movements is usually site-, season-, and species-specific, depending on the effect of hydraulic boundary conditions (e.g., roughness of the ramp surface, conditions at the ramp toe related with erosion processes, and/or structure maintenance), hydrodynamics (e.g., water depth, discharge, and turbulence) present in the vicinity of the structure (Baudoin et al. 2014; Harris et al. 2016), and on fish swimming abilities, which are closely related to fish species groups and body size (Kemp and O'Hanley 2010; Katopodis and Gervais 2016; Newton et al. 2018). Nevertheless, in the physical design of a ramped weir, length and slope play an important role on the efficiency of these structures to successful upstream passage of fish (Schmutz and Mielach 2013; Baker 2014; Baudoin et al. 2014). As mentioned by Baker (2014), although the effect of ramp length and slope is difficult to discriminate and their relative contribution has seldom been assessed, it is particularly important to study the interaction of these key factors in order to establish more appropriate design considerations for these types of obstacles.

The goal of this study was to assess the passage performance of a medium-size potamodromous cyprinid, the Iberian barbel, *Luciobarbus bocagei* (Steindachner, 1864), negotiating an experimental low-head ramped weir with varying ramp length (L) and slope (S). Iberian barbel was selected as the target species for being considered a representative of several species from the genera *Barbus* and *Luciobarbus*, commonly present in rivers from Mediterranean and Western Europe (Santos et al. 2014; Romão et al. 2018). It is expected that (i) passage performance of fish, considering the attraction as well as upstream successful passages, will be influenced by the different combinations of L and S; (ii) attraction efficiency would increase with increasing L and S, due to increasing water velocity near the ramp that may act as an attraction factor for fish; and (iii) successful passages, and consequently passage efficiency, would decrease with increasing L and increasing S, hampered by the increasing water velocity present downstream and over the ramped weir.

1.3. Material and Methods

Overall, To study the influence of L and S on the passage performance of Iberian barbel, four configurations encompassing two ramp lengths (L = 1.50 and 3.00 m) and three different slopes (S = 10%, 20%, 30%) were assessed (L150 S10; L150 S20; L150 S30; L300 S10). The experimental ramped weirs (Figure 1.1A), made of maritime plywood, were tested in an indoor ecohydraulic flume (a rectangular steel frame 10.00 m long × 1.20 m high × 0.60 m wide, with glass-viewing panels on sidewalls that allow direct observation of fish where, due to its dimensions and facilities, it is possible to preform ecohydraulic studies, assessing the influence of key hydraulic variables on the behaviour of specimens) installed at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon. The flume (Figure 1.1B) includes an upstream and a downstream tank, separated from the channel by mesh panels (from where the water enters the flume and is recirculated), and it was tilted at a 3% slope to represent the average slope of central and southern Iberian rivers (Catchment Characterisation and Modelling, version 2 [CCM2]; Vogt et al. 2007). The experimental ramped weir (Figure 1.1B), spanning the entire channel width, was fixed in the flume at 2.50 m upstream of the acclimation area, a 0.60 m^2 area created by two mesh panels in the downstream zone of the flume. Immediately downstream of the ramp toe, a zone 0.50 m in length was established as the approach area. Discharge was measured by a flow meter installed in the supply pipe and maintained constant at 110 $L.s^{-1}$. Consequently, in all the configurations tested, the water depths at the weir crest and along the ramps, measured using rulers placed along the glass-viewing panels of the channel, were similar. Values registered at the weir crest varied from 0.19 to 0.20 m (observed in L150 S10 and L300 S10, respectively). Along the ramp, water depths decreased from 0.10–0.11 m (registered in L300 S10 and L150 S10, respectively), registered at the upper part of the ramp, to 0.06–0.08 m (observed in L150 S30 and L150 S10, respectively). A minimum water depth of 0.20 m, which was found to be the most suitable according to literature (FAO/DVWK 2002; Baudoin et al. 2014) and previous studies by Amaral et al. (2016; 2018), was maintained in the approach area to standardize that condition throughout the experiments. Since the water column over the tested ramps was not deep enough (≈ 0.10 m) to use a 3D acoustic Doppler velocimeter and there was too much aeration and turbulence downstream of the ramp, especially at the ramp toe, the water velocity along the ramps, as well as upstream and downstream of the ramp, was instead measured with a flow probe (model FP 101, Global Water Instrumentation) in 21 and 27 sampling points for L = 1.50 m and L = 3.00 m, respectively. Sampling points were established along three longitudinal planes – a plane along the centre of the ramp and two lateral planes spaced 0.05 m from the walls, and at intervals of 0.75 m along the ramp. Measurements were also taken in the middle of the weir crest, as well as 0.50 m upstream and downstream (0.50 and 1.00 m) of the ramped weir. These measurements (Vx) were represented graphically by contour maps, to illustrate water velocity variation along the tested combinations.

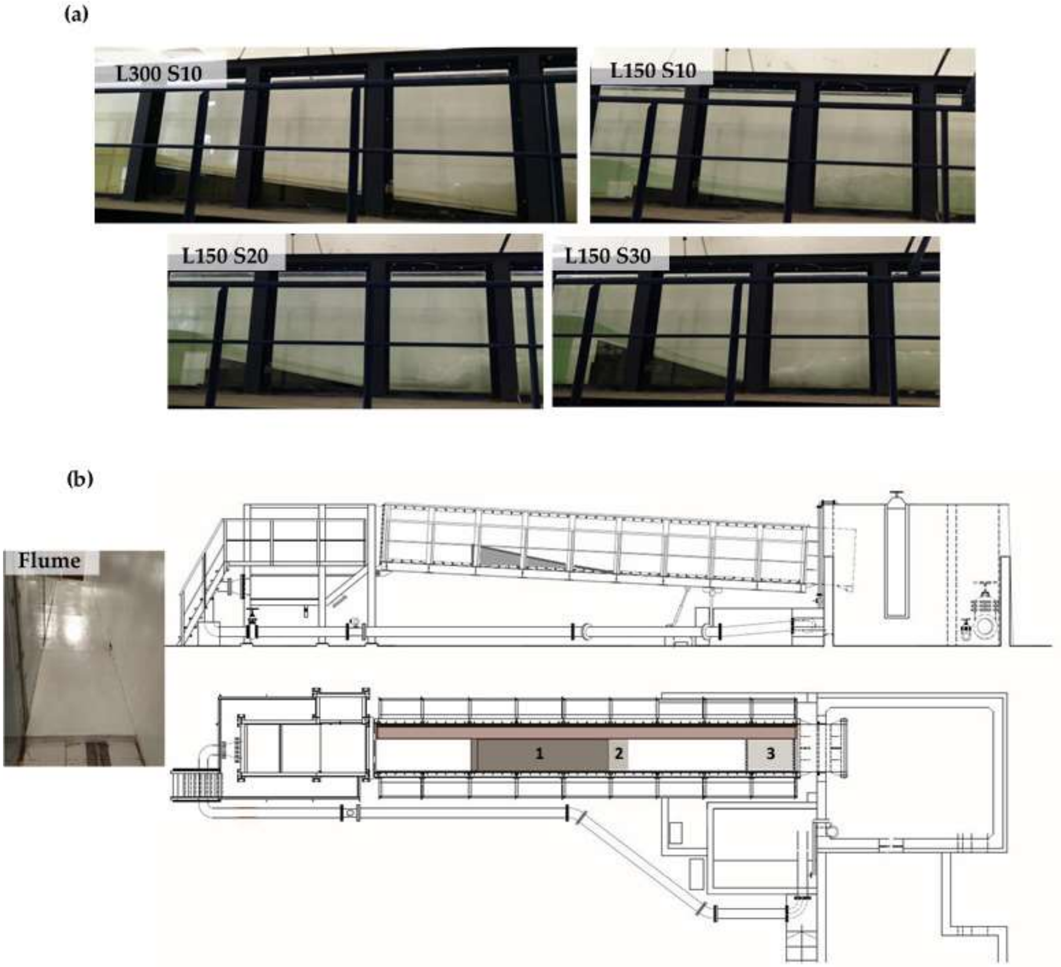

Fig. 1.1. Images of (a) the four configurations tested (L represents the length (cm), while S the slope (%) of the ramp); (b) the experimental flume, representing a side view of the channel on a slope of 3% (scheme above), and a top view (scheme below) with the location of (1) the experimental low-head ramped weir (2.50 m upstream the acclimation area), (2) the approach area (the 0.30 m^2 shaded area immediately downstream of the ramp toe), and (3) the acclimation area (the 0.60 m^2 shaded area between the two removable fine mesh panels located downstream).

Adult Iberian barbel used in the experiments (n = 80; mean total length (TL) ± standard deviation (SD) = 16.3 ± 2.1 cm) were captured by wadeable electrofishing (Hans Grassl IG-200) in the Lisandro River, a small Atlantic coastal river near Lisbon. Fishing and handling permits for capture of wild fish (40/2017 and 222/2017/CAPT; 41/2017 and 223/2017/CAPT; 42/2017 and 224/2017/CAPT, respectively) were issued by the Portuguese Institute for Nature Conservation and Forests (ICNF, I.P.). A total of four electrofishing episodes were performed (two episodes per week during two consecutive weeks to not bias the fish motivation, collecting 20 fish per episode) according to the protocol adopted by the European Committee for Standardization (CEN 2003). To transport the fish to the laboratory facilities at LNEC, a fish transport box (Hans Grassl, 190 L) with external aeration was used. At LNEC, fish were maintained in filtered and aerated acclimation tanks (700 L tanks; Fluval Canister Filter FX5), where water quality was daily monitored (temperature = 23 ± 1 °C, pH = 7.7 ± 0.1, and conductivity = 174 ± 14 $\mu s.cm^{-1}$), using a multiparametric probe (HANNA, HI 9812-5), and high-quality levels (i.e., active fish, no mortality) were guaranteed by the mechanical and biological filtration system, with a turnover rate of 2300 L.h^{-1}. Fish were only tested after an acclimation period of 48 h from the holding conditions in the laboratory.

The study was conducted in agreement with national and international guidelines to maintain the welfare of the tested animals and minimise stress (J. M. Santos holds FELASA Level C certification (www.felasa.eu) to direct animal experiments). Fish experiments and maintenance in the laboratory and experimental facility were authorized (reference DGAV: 0420/000/000/2012) by the Department for Health and Animal Protection (Direcção de Serviços de Saúde e Protecção Animal) in accordance with the recommendations of the "Protection of animal use for experimental and scientific work". No fish were sacrificed during this study and, after finishing the experiments, all fish were taken back and released in their natural habitat.

Experiments were performed during late spring–early summer, reported by some authors as the main reproductive season for this species (Santos et al. 2005; Baudoin et al. 2014). For each configuration tested (L150 S10; L150 S20; L150 S30; L300 S10), 4 replicates were carried out with schools of 5 fish (n = 20 fish) that were haphazardly selected from the acclimation tanks and were used only once. The unit of analysis was therefore a school of five adult Iberian barbel with similar size, as this species tends to move in schools, rather than individually, as observed in other studies by Amaral et al. (2016; 2018) and Romão et al. (2017; 2018), to increase hydrodynamic efficiency (Pitcher and Parrish 1993). For fish to adapt to the conditions in the flume, each replicate started with an acclimation period of 15 min (period previously tested by Amaral et al. (2016; 2018a; 2018b) and considered to be appropriate for the acclimation of fish to the flume). After that time, the upstream mesh panel of the acclimation area was removed, and fish were able to volitionally explore the channel for a maximum of 60 min. Since both upstream and downstream passages were allowed, fish could approach, attempt to pass, and successfully negotiate the ramp multiple times. Fish movements were monitored by direct observation and recorded (top view) by a video camera (GoPro HERO5). The number of fish that entered the approach area (Ap), the number of fish that entered into the ramp and actively tried to negotiate it (At), and the number of fish that completely passed the ramp to upstream, i.e., completed successful passages (N), were registered. Metrics of passage performance, such as percentage of attraction efficiency (AE%) and percentage of passage efficiency (PE%), were then calculated from Equations (1) and (2), adapted from Amaral et al. (2016). For the statistical analysis, because this study did not have a full factorial design, and data were not homoscedastic nor normally distributed, a nonparametric Kruskal-Wallis H test was performed to analyse the influence of L and S on the successful negotiation of the experimental ramps, pondering the results for N, AE%, and PE%. The *dunn.test* package (Dinno 2015), from the open-source software R (R Core Team 2017), was used to compute the analysis.

$$AE\% = 100 \times At/Ap \tag{1}$$

$$PE\% = 100 \times N/At \tag{2}$$

1.4. Results

Upstream successful passages were registered in all the configurations tested. However, the number of N, Ap, and At, and consequently values of AE% and PE%, varied according to the tested configurations, highlighting the effect that factors L and S may have had on the passage performance of Iberian barbel. The total number of N, together with values of PE%, mainly decreased with the increase of tested L (Figure 1.2A) and S (Figure 1.2B). On the contrary, values of AE% registered an increase with the increasing values of both L and S (Figure 1.2A,B). Configuration L150 S20 recorded the highest number of Ap, At, and N (totals of 31, 21, and 17, respectively), being the configuration with higher PE% (81%). On the other hand, configuration L150 S30 registered the lowest numbers, with only Ap = 15, At = 11, and N = 4. However, it was the most attractive configuration for fish, with AE% = 73.3%, followed by L300 S10 (71.4%), which in turn was the least efficient configuration in terms of PE%, registering only 15% (Ap = 28, At = 20, N = 3). Configuration L150 S10 was the least attractive for fish (AE% = 53.6%), registering several approaches (Ap = 28) but few attempts (At = 15) to negotiate the experimental ramp.

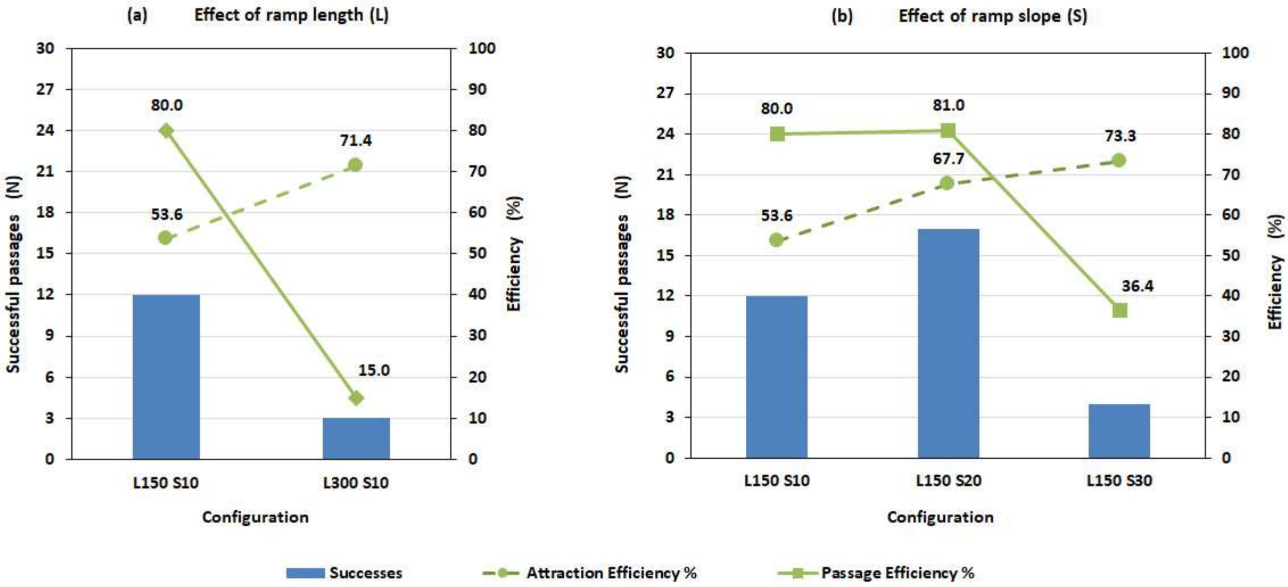

Fig. 1.2. Results for the number of successful passages (N; bars), and attraction efficiency (AE%; dotted line) and passage efficiency (PE%; solid line) for the configurations tested, considering the variation of (a) ramp length (L); (b) ramp slope (S).

Results from the Kruskal-Wallis *H* test suggest a marginally significant influence (i.e., $P \leq 0.10$) of both factors L and S on the number of N (L: $H = 1.85$, 1 *d.f.*, $P = 0.10$; S: $H = 4.47$, 2 *d.f.*, $P = 0.10$), as well as on values of PE% (L: $H = 3.19$, 1 *d.f.*, $P = 0.07$; S: $H = 5.71$, 2 *d.f.*, $P = 0.05$). The ramp with L = 1.50 m achieved better results than the one with L = 3.00 m and, in terms of slope, S = 20% stood out from the other slopes tested as the most successful. As for AE%, however, results reveal no significant influence of factors L ($H = 0.004$, 1 *d.f.*, $P = 0.90$) and S ($H = 2.30$, 2 *d.f.*, $P = 0.31$).

Figure 1.3 displays the variation of water velocity (V*x*) for the different tested ramps. Contour maps revealed that water velocity values increased with L and S. This increase was particularly important in the case of L150 S30 and L300 S10, where values of water velocity above 3 m.s^{-1} were registered close to the toe of the ramp. On the contrary, configuration L150 S10 was the one with the lowest water velocities (1.8 m.s^{-1} close to the toe of the ramp, and a maximum of 2.3 m.s^{-1} over the ramp).

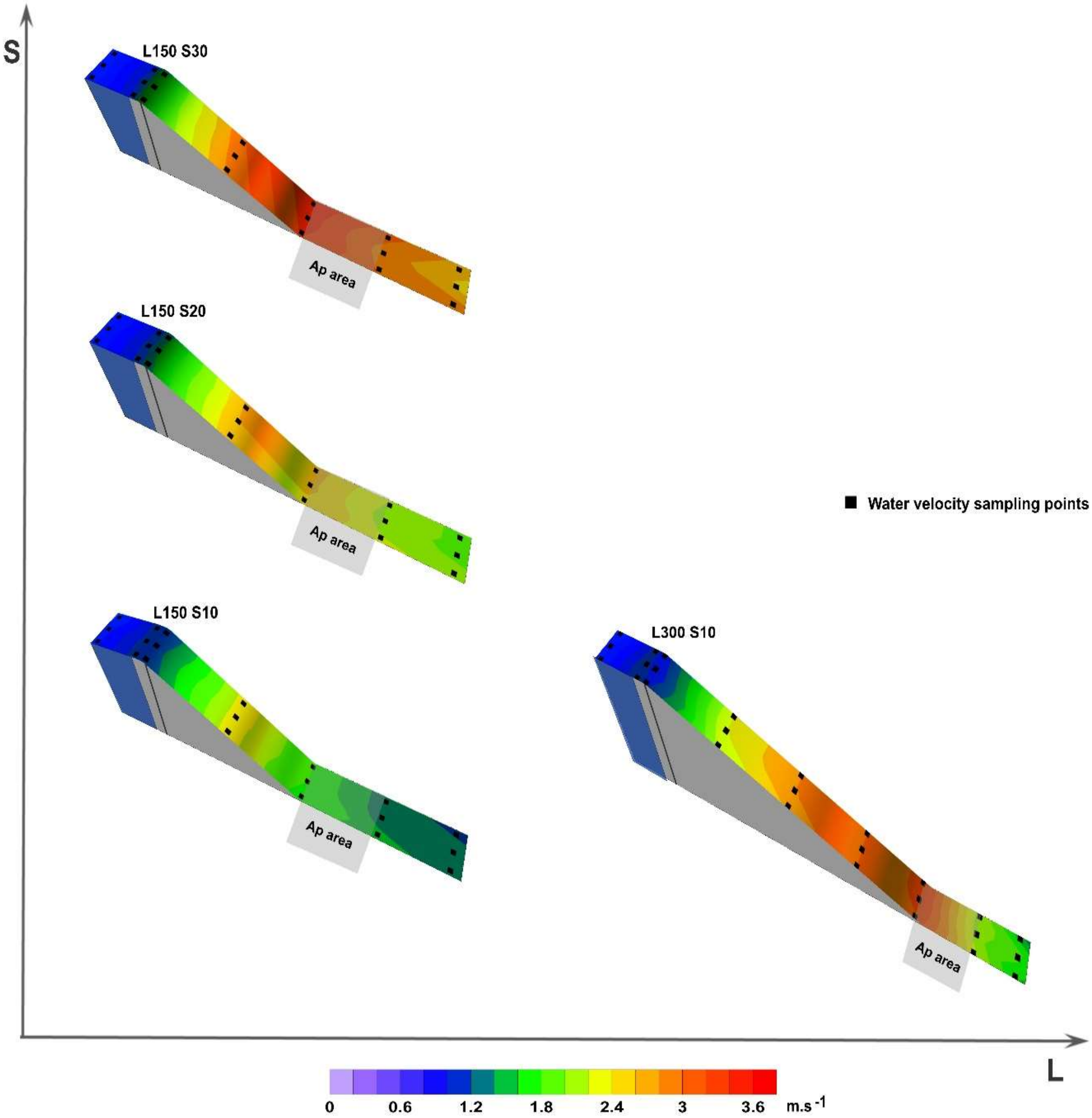

Fig. 1.3. Contour maps of water velocity (V*x*) for the configurations tested, considering the variation of ramp length (L) and slope (S). Measurements were made with a flow probe (model FP 101, Global Water Instrumentation). Black dots represent water velocity sampling points. The approach area, located immediately downstream of the ramp toe between two lines of sampling points, is identified by the tag below (Ap area).

1.5. Discussion

In situ studies on the negotiation of small instream obstacles by fish – that must associate the assessment of fish movements and an extensive characterization of all the hydrodynamic conditions that fish need to overcome in order to successfully pass the obstacle – can be very complex and onerous (Rice et al. 2010; Ordeix et al. 2011; Lacey et al. 2012). All the requirements needed to carry out such studies, in terms of human resources and time, field equipment, and robust technology, may strongly constrain their developments (Rice at al. 2010; Wang and Hartlieb 2011), unless a long period of execution and provision of funding is ensured, conditions that most scientific field experiments often fail to achieve. Therefore, the use of full-scale or even scaled-down laboratory facilities, such as the ecohydraulic flume used in the present study, is presented as a more expeditious parallel approach to study fish behaviour and negotiation of small instream obstacles (Kemp et al. 2006; Martin and Bateson 2007; Santos et al. 2014). Inherent to laboratory conditions, these ecohydraulic flumes provide the opportunity to easily manipulate important factors, control for confounding variables and effects that could bias the results, and observe responses that should improve the knowledge of events occurring in the wild (Kemp et al. 2006; Alexandre et al. 2013; Santos et al. 2014).

In this study, the influence of L and S on the passage performance of the Iberian barbel negotiating an experimental low-head ramped weir was assessed, maintaining a constant discharge of 110 $L.s^{-1}$. Although experimental conditions tested in the flume were a simplification of what fish may encounter in nature, they allowed detailed observation of fish behaviour (e.g., fish approaching the ramp, attempts to negotiate it, and successful passages) as well as the control and analysis of physical and hydraulic variables, such as ramp length and slope, discharge and consequently water velocity, and water depth at the toe of the ramp that, along with fish swimming abilities and other boundary conditions (e.g., roughness of the ramp surface, structural conditions of the ramp toe), are referred by some authors (Solà et al. 2011; Schmutz and Mielach 2013; Baker 2014; Baudoin et al. 2014; Harris et al. 2016) as preponderant factors for the successful upstream passage of fish along ramped weirs.

Results of this experiment suggest that both factors L and S had a marginally significant influence on the number of N, and consequently on values of PE%, but their influence on AE% was not significantly determined. As in other experiments by Amaral et al. (2016; 2018b), and in Goerig and Castro-Santos (2017), the “fish passage paradox” – concerning the influence of water velocity and, consequently, of turbulence and energy dissipation present on these small barriers (Schmutz and Mielach 2013; Baudoin et al. 2014) in the attraction of fish and on the successful negotiation of the obstacle – was also observed in the present study. Fish were attracted to the ramped weir by high values of water velocity but, at the same time, it might have been a limiting factor for successful upstream passage – what attracts fish is what hampers movements.

Contrary to what was initially expected, configuration L150 S10, that combined the smallest L with the lowest S, and thus the one that registered the lowest values of water velocities, was not the configuration that recorded the highest values of N or PE%, and was also the least attractive (AE% ca. 50%). In this configuration, only half the fish that entered the approach area (Ap = 28) went into the ramp and actively tried to negotiate it, a fact that may suggest that the water velocity (Vx = 1.7 $m.s^{-1}$) was not the most appropriate to establish an attractive path for fish to proceed and successfully pass the obstacle (Pavlov et al. 2000; Elder and Coombs 2015; Goerig and Castro-Santos 2017). On the other hand, configurations L150 S30 and L300 S10, which displayed high water velocity (registering values of 3.6 and 3.4 $m.s^{-1}$, respectively, at the ramp toe) due to the correspondingly steeper S and the longer L, achieved the highest values of AE% but registered a low number of N (only 4 and 3 successful passages, respectively) and, consequently, the lowest values of PE% (36% and 15%, respectively), suggesting that water velocity, and the potential turbulence associated to these type of obstacles (Schmutz and Mielach 2013; Baudoin et al. 2014), had a positive influence on the attraction of fish to the ramp but, at the same time, might have hampered their successful upstream passage possibly due to fish disorientation and fatigue (Pavlov et al. 2000; Liao 2007; Elder and Coombs 2015). This was especially observed in configuration L300 S10 where, in some attempts, fish were able to negotiate the ramp up to its half-length by sprinting (maximum-speed swimming), overcoming values of water velocity around 3 $m.s^{-1}$. However, most likely due to fatigue, fish stopped swimming and were dragged down to the end of the ramp. Therefore, to enhance fish passage along long low-head ramped weirs, it would probably be important to retrofit these types of obstacles with substrates, such as different types of blocks or rocks for a more nature-like design, in order to create areas with diverse hydraulic conditions along the ramp (Baki et al. 2016; Muraoka et al. 2017), allowing fish to rest and to recover energy to continue successful negotiation of the ramp (Katopodis and Gervais 2016; Muraoka et al. 2017). Since the swimming performance of the Iberian barbel is quite similar to the swimming performance of other rheophilic cyprinids and salmonids of the same length (Katopodis and Gervais 2016), these results may be more broadly applicable. Nevertheless, species swimming traits and the different strategies to negotiate obstacles should always be considered (Romão et al. 2012; Aramburu et al. 2016; Romão et al. 2017). Finally, configuration L150 S20, which displayed intermediate values of water velocity when compared to the other configurations tested, was the combination that recorded the best results for N and PE%, and registered also nearly 70% of AE%, a value that may be considered as a reasonable percentage for attraction. Taken together, these results may suggest that, upon designing ramped-weirs, configurations with the lowest slopes may not necessarily be the best option, because they are less attractive for the fish and their demand for space is higher, thereby increasing construction costs. Conversely, as the present study shows, higher (but not excessive) slopes, though yielding a similar PE%, can be more attractive to fish, less expensive and, therefore, more cost-effective.

In conclusion, this study is in line with the outcomes of Baker (2014) about the importance that L and S may have on the permeability of low-head ramped weirs for upstream movements of fish, both in terms of the attraction of fish to the ramp and especially regarding successful negotiation. However, the negotiation of ramped weirs by potamodromous fish species should be further investigated. Future studies should explore discharge variation and boulder placement, featuring different arrangements and geometries that influence fish passage across low-head ramped weirs, to further improve habitat connectivity. Thereby, the outcomes from the present work, complemented with future research pondering the above considerations, may significantly contribute to help engineers and biologists to design more appropriate passage structures for low-head instream obstacles.

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2. Assessment of retrofitted ramped weirs to improve passage of potamodromous fish

Amaral, S.D.; Quaresma, A.L., Branco, P.; Romão, F., Katopodis, C.; Ferreira, M.T.; Pinheiro, A.N.; Santos, J.M. 2019. Assessment of retrofitted ramped weirs to improve passage of potamodromous fish. Water, 11. 2441. https://doi.org/10.3390/w11122441

2.1. Abstract

The addition of substrates to small instream obstacles, like low-head ramped weirs, has been considered a useful management solution to retrofit those structures and enhance upstream fish passage. Substrate dimensions and spatial arrangement, together with discharge, and consequently water depths, appear to be important factors for the creation of suitable hydrodynamic conditions that may facilitate the successful passage of fish, though related studies are scarce to support decision making. This study assessed the influence of discharge (Q) and different retrofitting designs (RD) on the upstream passage performance of a potamodromous cyprinid, the Iberian barbel (*Luciobarbus bocagei*). Different types of substrates (small boulders, large boulders, and cobbles) and spatial arrangements (aligned and offset) were considered. Numerical modelling, using the Computational Fluid Dynamics (CFD) commercial software FLOW-3D®, was performed to characterize the hydrodynamics of all the configurations tested, and identify areas of high velocity and turbulence gradients that might have affected fish movements. Results indicate that both factors, Q and RD, played an important role on the creation of suitable hydrodynamics for the upstream successful negotiation of ramped weirs. The RD with cobbles randomly distributed along the ramp (Nature design) was the most successful configuration, recording the highest number of successful upstream passages. Low velocity magnitudes along the ramp, and especially low turbulence downstream, for both Q values tested, were registered in this configuration. Therefore, the use of natural substrate like cobbles, may help to increase the permeability of ramped weirs to fish movements, by providing an effective energy dissipation along the obstacle. Nevertheless, the outcomes from the present work should be complemented with further research, including in-situ, on passage performance and hydrodynamics of low-head ramped weirs, encompassing other fish species, with different ecological traits, and a different range of discharges, to help engineers and biologists design more appropriate passage structures for low-head instream obstacles.

2.2. Introduction

Freshwater fish are among the most threatened species, especially due to flow modification and habitat destruction or degradation (Nilsson et al. 2005; Gozlan et al. 2019; Reid et al. 2019). The presence of small engineered structures (e.g. low-head weirs, culverts) has been considered one of the main causes to habitat fragmentation on rivers worldwide. Recent studies have pointed the fact that, due to the high abundance of these small obstacles, which are far more numerous than large dams (Lucas et al. 2009), their cumulative impact on fish populations may be greater than estimated (Baudoin et al. 2014; Branco et al. 2017; Birnie-Gauvin et al. 2019).

More than 8000 small weirs (height < 5 m) have been located in Portuguese rivers (Ordeix et al. 2018). The small broad-crested weirs, which have a vertical downstream face (Baudoin et al. 2014; Amaral et al. 2016), and especially low-head ramped weirs, with inclined faces that fish may be able to negotiate by swimming (Solà et al. 2011; Baudoin et al. 2014), are the two most common designs (Branco et al. 2017). In fact, in order to enhance fish passability, some old broad-crested weirs which, after assessment, could not be removed, have undergone rehabilitation works to include ramps in their designs (e.g. FAO/DVWK, 2002; http://www.rhpdm.uevora.pt/index.html). This design reconfiguration enables water to pass over the ramp, not generating a waterfall (Solà et al. 2011; Baudoin et al. 2014), a condition that may afford a more holistic negotiation by fish (Baker 2014; Baudoin et al. 2014). Nevertheless, fish swimming abilities, which are closely related to fish guilds and body size (Kemp and O'Hanley 2010; Sanz-Ronda et al. 2015; Katopodis and Gervais 2016; Newton et al. 2018), and hydrodynamic conditions, such as water depth, discharge and turbulence present over the ramp and in the vicinity of the structure (Ovidio et al. 2007; Baudoin et al. 2014; Harris et al. 2016; Knapp et al. 2019), are key factors that influence the permeability of such structures to fish movements.

The addition of substrates to instream obstacles and fish transposition devices, commonly referred to as retrofitting, has been considered a useful management solution to enhance upstream fish passage (Santos et al. 2013; Baudoin et al. 2014; Santos et al. 2014; Muraoka et al. 2017; Rodgers et al. 2017; Goodrich et al. 2018; Plesiński et al. 2018; Wang and Chanson 2018; Johnson et al. 2019). The placement of substrates in culverts to mimic natural stream conditions and facilitate fish passage has been successfully implemented since the early 1970s (Katopodis and Aadland 2006). In low-head ramped weirs, natural substrates like pebbles, cobbles or boulders, are frequently used as retrofitting solutions to increase bed roughness, and consequently promote energy dissipation, creating localized zones of low-velocity and turbulence (Towler et al. 2015; Muraoka et al. 2017; Rodgers et al. 2017; Plesiński et al. 2018) that may be used by fish as resting areas during the upstream negotiation of ramps (Liao 2007; Elder and Coombs 2015; Landsman et al. 2018; Wang and Chanson 2018; Knapp et al. 2019). These low velocities may be especially important to species of weaker swimming capabilities, such as potamodromous cyprinids (Santos et al. 2013; Baudoin et al. 2014; Santos et al. 2014). Substrate dimensions and spatial arrangement, together with discharge, and consequently water depths, appear therefore as important factors for the creation of suitable hydrodynamic conditions that may facilitate the successful upstream passage of fish (Muraoka et al. 2017; Johnson et al. 2019; Knapp et al. 2019). Nonetheless, the effectiveness and efficiency of most retrofitting solutions remains poorly understood, particularly for potamodromous cyprinids, which are an important component of Mediterranean fish assemblages (Hughes et al. 2010; Santos et al. 2011; Benitez et al. 2015).

This study aims to assess the influence of discharge (Q) and different retrofitting designs (RD) to improve upstream passage performance of the Iberian barbel [*Luciobarbus bocagei* (Steindachner, 1864)]. We have considered 4 configurations of Boulders placed on the sloped face of an experimental ramped weir, varying on size (Small vs. Large) and arrangement (Aligned vs. Offset). Two additional configurations were further considered: a Control (smooth bottom, no substrate) as the reference situation to assess potential improvements on fish passage, and a nature-like, hereafter referred to as Nature, consisting of cobbles randomly distributed along the ramp, as another potential improvement for fish passage (Katopodis and Williams 2012), giving a total of 6 configurations, tested under two different Q: 55 and 110 L.s^{-1}. Additionally, numerical modelling was performed to characterize the hydrodynamics of all the configurations tested, using the Computational Fluid Dynamics (CFD) commercial software FLOW-3D®. Iberian barbel was selected as the target species, since it is considered representative of a few species of medium-sized benthic potamodromous cyprinids commonly present in Iberian and Western European rivers (Santos et al. 2014; Romão et al. 2018). It was expected that: i) passage performance of fish, considering attraction as well as successful upstream movements, will be influenced by both factors Q and RD; ii) attraction efficiency would increase with increasing Q, and with RD that provide higher velocity magnitudes; and iii) successful passages, and consequently passage efficiency, would decrease with increasing Q and with RD presenting high turbulence and high velocity magnitude.

2.3. Material and Methods

2.3.1. Experimental facility

Experiments were performed in an indoor ecohydraulic flume installed at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon. The rectangular steel frame flume (Figure 2.1A), 10.00 m long × 0.60 m wide × 1.20 m high, comprises an upstream and a downstream tank, from where the water enters the flume and is recirculated, that are separated from the main channel by mesh panels. The sidewalls of the main channel are glass-viewing panels that allow a direct, and unobtrusive, observation of fish behaviour throughout the experiments. In order to represent the average slope of central and southern Iberian small size watercourses, the channel was set at a 3% slope (Catchment Characterisation and Modelling, version 2 [CCM2]; Vogt et al. 2007).

The experimental low-head ramped weir used in this study, with a length of 3.00 m and a slope of 10%, was selected based on the results of a previous study by Amaral et al. (2019), in which it was found that this combination of ramp length and slope may have adversely affected successful negotiations for the same species. As in Amaral et al. (2019), the experimental ramped weir, made of maritime plywood, was fixed in the flume (Figure 2.1A) at 2.50 m upstream of the acclimation area, a 0.60 m2 area created by two mesh panels in the downstream zone of the flume, and immediately downstream of the ramp toe, a 0.50 m long zone was established as the approach area. Six different configurations (Figure 2.1B) were tested, considering a Control ramp, without substrates, and five retrofitted designs contemplating: a Nature design, where cobbles of 10 to 30 cm were randomly distributed along the ramp; Small Boulders Aligned and Small Boulders Offset, using boulders 7.5 cm long × 7.5 cm wide × 15 cm high, spatially aligned and alternating respectively; and Large Boulders Aligned and Large Boulders Offset, where larger boulders (25 cm long × 7.5 cm wide × 30 cm high) were set in an aligned and alternating design respectively. Figure 2.2 illustrates the spatial arrangement of substrates on the retrofitted designs tested. Furthermore, to assess the influence of Q on the passage performance of fish, the six configurations were tested under two different discharges – 55 and 110 $L.s^{-1}$. The lower discharge (Q = 55 $L.s^{-1}$) was selected considering the recommendations by Baudoin et al. (2014) that suggests that the minimum water column over the ramp, referred as non-limiting for the successful upstream passage of fish, should be between one and two times the body depth of the fish. Regarding the higher discharge (Q = 110 $L.s^{-1}$; double the lower Q), which was previously tested by Amaral et al. (2019), it was selected to test the effect that higher water velocities and turbulence may have on hydrodynamics of different RD and, consequently, on the passage performance of fish. Discharge was measured by a flow meter installed in the supply pipe.

2.3.2. Fish capture and holding

Adult Iberian barbel used in the experiments (n = 240; mean total length (TL) ± standard deviation (SD) = 17.4 ± 2 cm; maximum body depth (H) ± SD = 3 ± 0.3 cm; body width (W) ± SD = 1.9 ± 0.3 cm) were captured by wadeable electrofishing (Hans Grassl IG-200) in the Lisandro River, a small Atlantic coastal river near Lisbon. A total of six electrofishing episodes were performed (one episode per week, collecting 40 fish per episode) according to the protocol adopted by the European Committee for Standardization (CEN 2003). Only adult fish were selected to avoid bias in swimming performance. Fish were transported to the laboratory facilities at LNEC in a fish transport box (Hans Grassl, 190 L) with portable external aeration (ELITE, Germany), and were maintained for a maximum period of 6 days in filtered and aerated acclimation tanks (700 L tanks; Fluval Canister Filter FX5), each featured with two U-shape ceramic roof tiles (45 cm long x 25 cm wide x 10 cm high) to provide shelter (Stammler and Corkum 2005). Water quality of the tanks was monitored daily (temperature = 22 ± 1 °C, pH = 7.7 ± 0.3, and conductivity = 180 ± 15 $\mu s.cm^{-1}$), using a multiparametric probe (HANNA, HI 9812-5), and high-quality levels (i.e. active fish, no mortality) were ensured by the mechanical and biological filtration system, with a turnover rate of 2300 $L.h^{-1}$. Fish were only tested after an acclimation period of 48 hours from the holding conditions in the laboratory. During that period, fish were fed with Tetra Pond sticks up to 24–48 h before the experiments. No fish were sacrificed during the experiments, and efforts were made to minimize stress.

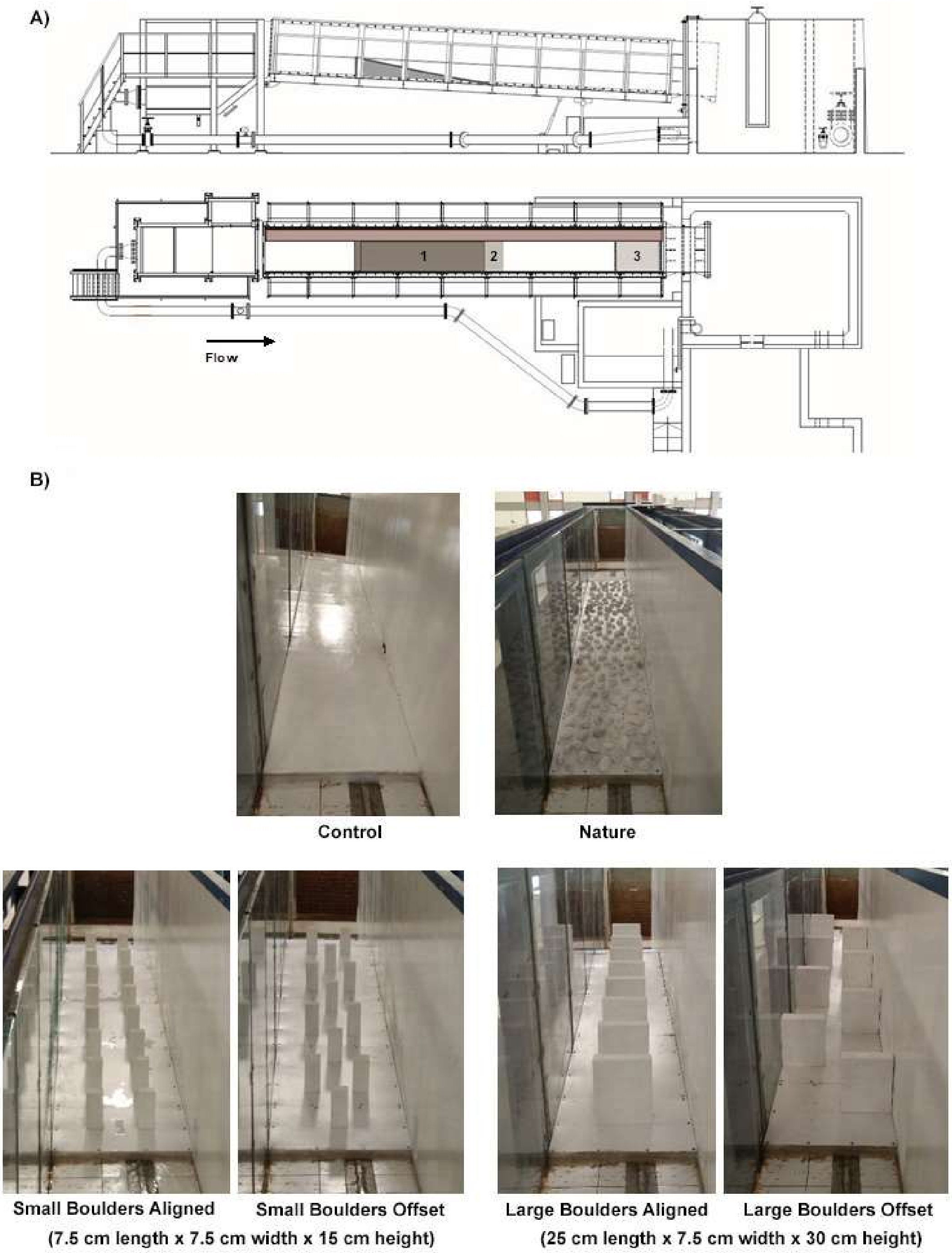

Fig. 2.1. A) Scheme of the experimental flume, representing a side view of the channel on a slope of 3% (above), and a top view (below) with the location of (1) the experimental low-head ramped weir (ramp 3.00 m long on a slope of 10%, with a 0.20 m weir crest, located 2.50 m upstream the acclimation area), (2) the approach area (the 0.30 m2 shaded area immediately downstream of the ramp toe), and (3) the acclimation area (the 0.60 m2 shaded area between the two removable fine mesh panels located downstream); B) Images of the six configurations tested, contemplating the Control ramp (without substrates) and the retrofitted designs selected: Nature (ramp with cobbles randomly distributed), Small Boulders Aligned and Offset (boulder dimensions 7.5 cm long × 7.5 cm wide × 15 cm high), and Large Boulders Aligned and Offset (boulder dimensions 25 cm long × 7.5 cm wide × 30 cm high).

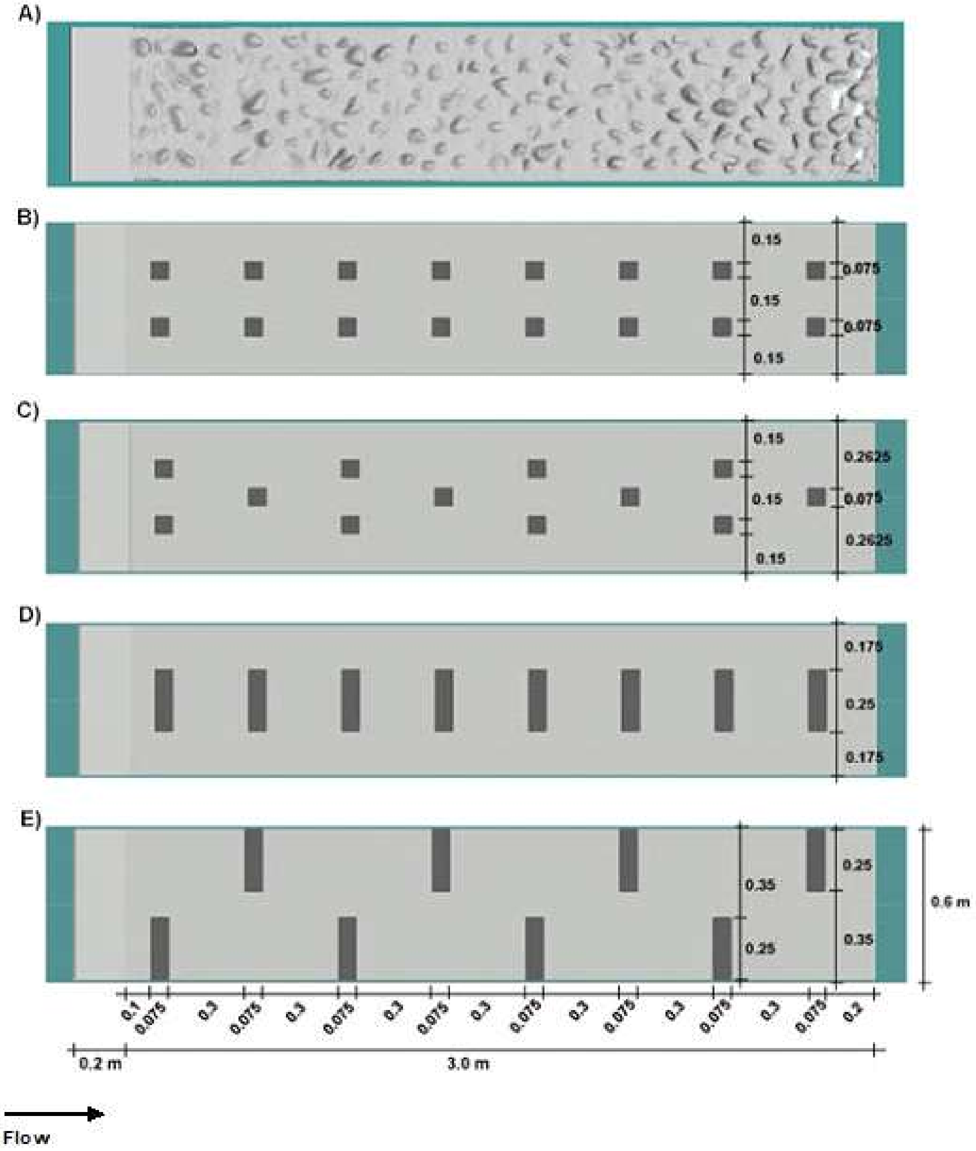

Fig. 2.2. Scheme of the substrates arrangement for the retrofitted designs (RD), showing flow direction and the 0.2 m weir crest: A) Nature (the mapping of cobbles along the ramp was done using a Kinect Sensor); B) Small Boulders Aligned; C) Small Boulders Offset; D) Large Boulders Aligned; E) Large Boulders Offset. Substrates dimensions: Cobbles – 10 to 30 cm; Small Boulders – 7.5 cm long × 7.5 cm wide × 15 cm high; Large Boulders – 25 cm long × 7.5 cm wide × 30 cm high.

2.3.3. Fish experiments

Fish experiments were conducted in strict accordance with ethical provisions on the welfare of experimental animals enforced by the European Union and were coordinated by J.M. Santos, who holds FELASA level C certification (www.felasa.eu) to direct animal experiments. Fish capture, handling, transportation and holding permits were issued by the Institute for Conservation of Nature and Forests (ICNF) (permit numbers 40/2017 and 222/2017/CAPT; 41/2017 and 223/2017/CAPT; 42/2017 and 224/2017/CAPT). Fish experiments and maintenance in the LNEC facility were authorized by the Department for Health and Animal Protection (Direcção de Serviços de Saúde e

Protecção Animal) in accordance with the recommendations of the "protection of animal use for experimental and scientific work".

Experiments were performed during late spring-early summer, reported by some authors as the main reproductive season for this species (Santos et al. 2005; Baudoin et al. 2014), following the previous findings by Amaral et al. (2019). Four replicates were carried out for each configuration tested (6 configurations × 2 discharges × 4 replicates = 48 trials) using schools of 5 fish (20 fish tested per configuration) with similar size, which were not individualized. Fish were randomly selected from the acclimation tanks and were used only once. Each replicate started with an acclimation period of 15 minutes, for fish to adapt to the flume conditions. After that time, the upstream mesh panel of the acclimation area was removed, and fish were able to explore the channel for 60 minutes. Both upstream and downstream passages were allowed, so fish could approach, attempt to pass, and successfully negotiate the ramp multiple times.

Fish movements, specifically the number of fish that entered the approach area (Ap), the number of fish that entered into the ramp and actively tried to negotiate it (At), and the number of fish that navigated the entire ramp reaching the upstream part of the flume – complete successful passages (S), were monitored by direct observation, and also recorded (top view) by a video camera (GoPro HERO5). The metrics of passage performance – percentage of attraction efficiency (AE; %) and percentage of passage efficiency (PE; %), were also calculated from Equations 1 and 2.

$$\text{AE}\ (\%) = 100 \times \text{At} / \text{Ap} \qquad (1)$$

$$\text{PE}\ (\%) = 100 \times \text{S} / \text{At} \qquad (2)$$

The influence of factors RD and Q, as well as their interaction, on the passage performance of Iberian barbel, considering the movements of Ap and At, as well as S, was analysed performing a PERMANOVA test, using the package PERMANOVA for PRIMER +v6.0 (Anderson et al. 2008). This statistical test was selected for being a robust non-parametric method based on permutations tests that directly partitions the variation in a distance matrix according to Euclidean distances or non-Euclidean-embeddable dissimilarity measures (Anderson 2001; Anderson 2017). In this analysis, the Euclidean distance was applied to compute the distance matrix due to the presence, and relevance, of zeros in the assessed data (Anderson et al. 2008).

2.3.4. Hydrodynamic modelling

The hydrodynamics of the tested configurations were characterized by numerical modelling using FLOW-3D®, a computational fluid dynamics (CFD) commercial software. FLOW-3D® uses the finite volume method to solve the governing equations of fluid motion, by subdividing the computational domain into a structured mesh grid of variable-sized hexahedral cells, using a volume of fluid (VOF) method to track the free surface (Hirt and Nichols 1981; Flow Science 2016). The Fractional Area/Volume Obstacle Representation (Hirt and Sicilian 1985), named FAVORTM method, is one of the major features of FLOW-3D®. This method is used to represent obstacles through fractional areas and volumes in the fixed orthogonal grid. Flow Science (2016) presents additional details regarding the theoretical and numerical fundamentals of FLOW-3D®, which has been used in recent years to characterize flow hydrodynamics in ecohydraulics and fishway research (e.g. Duguay and Lacey 2016; Kolden et al. 2016; Quaresma et al. 2018).

The computational domain was discretized using two grid blocks: one, with a uniform mesh size of 0.01 m that contained the entire flume geometry, and one nested block with half the grid spacing (0.005 m) from the upstream face of the weir to 0.5 m downstream the ramp. Data on spatial arrangement of the tested configurations – Control, Small Boulders Aligned, Small Boulders Offset, Large Boulders Aligned and Large Boulders Offset, was generated using AutoCAD and was imported into the model as stereolithography (STL) files. For the Nature design, the 3D-bottom bathymetric data was measured using Kinect^{TM}, an input device designed for the Microsoft® Xbox 360® (Mankoff and Russo 2013). The upstream boundary was specified as a constant volume flow rate with the initial inlet water level defined as the water depth observed in the experimental flume, and the downstream boundary was specified as a pressure boundary condition, based on the water depth observed in the trials. The side walls and the bottom were modelled as smooth no-slip boundaries, and, at the top, a symmetry boundary condition (zero value for normal velocity, zero gradients for the other quantities) was applied. The initial pressure was set to the atmospheric pressure. A second order monotonicity preserving method and the large-eddy simulation (LES) model was employed for the momentum advection equations and the turbulence modelling and an implicit generalized minimum residual method solver (GMRES) was used (Flow Science 2016). The simulations were performed for a number of time steps enough to achieve a statistically stationary solution and obtain converged time-averaged values.

Model performance was validated with values of water depth and velocity magnitude measured during experiments in 27 sampling points (Figure 2.3), located along the ramped weir and both up and downstream (more details in Amaral et al. 2019). Velocity magnitude was measured with a flow probe (model FP 101, Global Water Instrumentation), since water column was not deep, and there was excessive aeration and turbulence in most of the configurations tested, conditions that narrow the use of a 3D acoustic doppler velocimeter. To check the influence of the grid resolution on the results, a coarser mesh (2.5 million cells), which doubled the size of the mesh cells (by halving the number of cells in each direction), was tested for the Control configuration. The LES Index of Resolution Quality (LES IQ), proposed by Celik et al. (2005), and mean absolute differences (*MAD*) were computed in the 27 sampling points, where water depth and velocity magnitude were measured, to verify the numerical model quality.

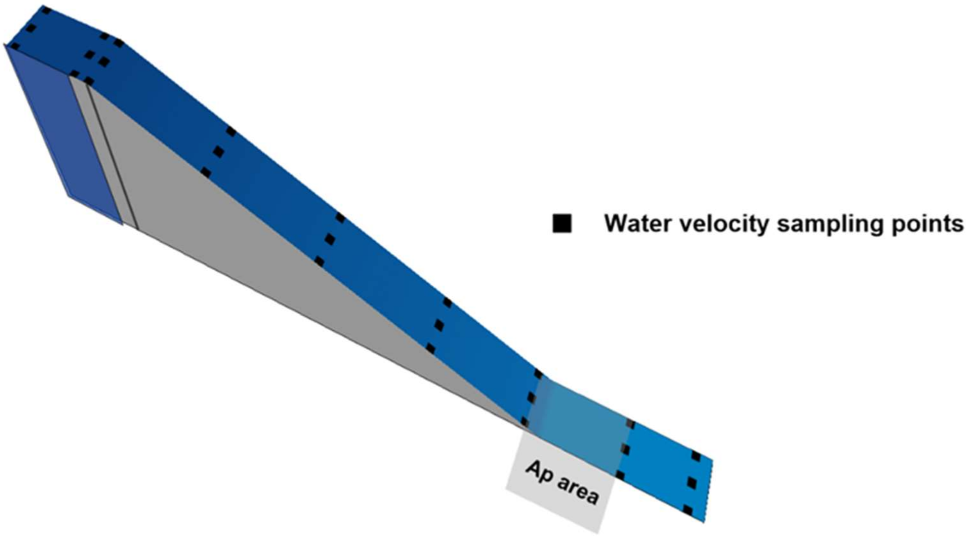

Fig. 2.3. Location of the water velocity sampling points. Measurements were taken along 3 longitudinal planes – at the center of the ramp, and 2 lateral planes spaced 0.05m from the walls. Points were distanced 0.75 m along the ramp, and 0.50 m upstream and downstream (0.50 m and 1.00 m) of the ramped weir. Water velocity at the middle of the weir crest was also measured.

Finally, to illustrate the hydrodynamic conditions formed in each configuration tested (e.g. areas of high velocity and turbulence gradients that might have affected fish movements), 3D contour maps, representing the mean velocity magnitudes ($\overline{U}$; m.s^{-1}) and turbulent kinetic energy per unit mass (TKE; m^{2}.s^{-2}), calculated from Equations 3 and 4 respectively, were plotted using the post-processing tool FlowSight. Mean water depths over the ramp ($\overline{h}$; cm) were also calculated.

$$\overline{U} = (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})^{1/2}, \qquad (3)$$

$$\text{TKE} = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right), \qquad (4)$$

2.4. Results

2.4.1. Fish movements

Numerous movements of approach and attempts to negotiate the experimental ramps, as well as upstream successful passages, were registered in all configurations tested. However, results from the different RD and Q tested (Table 2.1) were considerably different.

In general, more movements of Ap (n = 3010) and At (n = 437) were observed with Q = 55 L.s^{-1}, relative to 110 L.s^{-1} (1385 and 200, respectively). Regarding S, more successes (n = 50) were also registered with Q = 55 L.s^{-1} when compared to 110 L.s^{-1} (n = 36), except for the two designs using the small boulders, in which only one successful passage was registered in the configuration Small Boulders Aligned, and no successes were attained in the Small Boulders Offset configuration.

Concerning Q = 110 $L.s^{-1}$, the poorest results were registered for the configurations Large Boulders Aligned and Control, with only 3 successes, and the total number of Ap (22 and 28 total approaches, respectively) and At (10 and 20 attempts to negotiate the ramp, respectively) observed in these configurations were also the lowest. For both discharges tested, the Nature design was the most successful configuration in terms of S, achieving 23 and 12 upstream passages for Q = 55 and 110 $L.s^{-1}$, respectively. Regarding the metrics of passage performance, although Q = 55 $L.s^{-1}$ registered an overall high number of fish movements, as mentioned above, AE (average of 46%) and PE (average of 4%) were lower than those recorded with Q = 110 $L.s^{-1}$ (average of 50% and 24%, respectively). The Nature design was, in general, the configuration most efficient, registering values of AE = 75% and PE = 8%, for Q = 55 $L.s^{-1}$, and PE = 48%, for Q = 110 $L.s^{-1}$. However, for Q = 110 $L.s^{-1}$, this configuration was the least attractive, registering the lowest value of AE (26%). In terms of PE, the poorest results were registered in the configurations Small Boulders Aligned (0% and 9%, for Q = 55 and 110 $L.s^{-1}$, respectively) and Small Boulders Offset (0% and 11%, for Q = 55 and 110 $L.s^{-1}$, respectively), for both discharges tested.

Table 2.1. Total number of attempts (At), approaches (Ap), upstream successful passages (S), as well as attraction efficiency (AE%; ratio of the number of attempts per number of approaches × 100) and passage efficiency (PE%; ratio of successful upstream passages per number of attempts × 100) for the control low-head ramped weir and the retrofitting designs (RD) selected, considering the tested discharges (Q) of 55 L.s-1 (first rows) and 110 L.s-1 (second rows).

			Retrofitting Designs (RD)				
	Q	**Control**	**Small Boulders Aligned**	**Small Boulders Offset**	**Large Boulders Aligned**	**Large Boulders Offset**	**Nature**
Ap	55	377	646	532	389	655	411
	110	28	155	103	22	34	95
At	55	132	300	178	153	314	308
	110	20	79	46	10	20	25
S	55	12	1	0	7	7	23
	110	3	7	5	3	6	12
AE %	55	35	46	34	39	48	75
	110	71	51	45	46	59	26
PE %	55	9	0	0	5	2	8
	110	15	9	11	30	30	48

Results of the PERMANOVA analysis indicated that the number of Ap and At were significantly influenced by RD (Ap: F = 2.99; P = 0.03; and At: F = 2.84; P = 0.03) and by Q (Ap: F = 74.13; P < 0.01; At: F = 122.18; P < 0.01), but the combination of these factors (RD × Q) was not influencing fish movements (Ap: F = 1.41; P = 0.24; At: F = 2.01; P > 0.05). Concerning the influence on S, results reveal that successes were significantly influenced by RD (F = 6.55; P < 0.01) and by the combination RD × Q (F = 2.82; P = 0.02), but the influence of Q per se was not confirmed (F = 1.86; P > 0.05). Results of the pairwise comparisons (Table 2.2), performed after the main PERMANOVA test, show that configurations had no differences in terms of S, except for Control vs. Small Boulders Offset, and especially for the Nature design, which registered more upstream successful passages when compared with all other configurations tested.

Table 2.2. Results of the pairwise comparisons, performed after the main test PERMANOVA, on the number of successful upstream passages (S) for the factor retrofitting design (RD). Bold values highlight significant differences (α = 0.05).

	Retrofitting Design (RD)				
P	**Control**	**Small Boulders Aligned**	**Small Boulders Offset**	**Large Boulders Aligned**	**Large Boulders Offset**
Small Boulders Aligned	0.22				
Small Boulders Offset	**0.01**	0.65			
Large Boulders Aligned	0.30	0.79	0.29		
Large Boulders Offset	0.72	0.45	0.12	0.65	
Nature	**0.02**	**0.01**	**< 0.01**	**0.01**	**0.02**

2.4.2. Hydrodynamics

Results from the LES IQ quality index show that the finer mesh has an average value of 0.86, for Q = 55 L.s-1, and 0.89, for Q = 110 L.s-1. According to Pope (2000), a good LES should have an LES IQ higher than 0.80, which means that 80% of the TKE was resolved. Thus, the values obtained for the finer mesh indicate that sufficient grid resolution was used. Regarding the results from *MAD*, computed from observed and modelled values, they ranged from 0.01 to 0.02 m for $\bar{h}$, registering a coefficient of determination (R^2) between 0.96 and 0.99. When comparing observed and modelled $\overline{U}$, *MAD* ranged from 0.2 to 0.3 m.s^{-1}, registering an R^2 between 0.75 and 0.90. Therefore, the numerical model accurately reproduced the laboratory experiments.

Three-dimensional contour maps, showing the variation of $\overline{U}$ (Figure 2.4) and TKE per unit mass (Figure 2.5) for the tested configurations, indicate that both hydraulic parameters increased with discharge. Moreover, Small Boulders Aligned, Small Boulders Offset, Large Boulders Aligned, and Large Boulders Offset, were configurations especially turbulent, registering values of TKE per unit mass above 0.4 m2.s^{-2}, even with Q = 55 L.s^{-1}. As for the configurations Control and Nature, lower values of TKE per unit mass (Control: < 0.3 m^2.s^{-2}, and Nature: < 0.25 m^2.s^{-2}) were registered, for both Q tested. However, in terms of $\overline{U}$, in both discharges tested, higher magnitudes were registered, as expected, in the Control configuration (max mean magnitude of 2.6 m.s^{-1} for Q = 55 L.s^{-1}, and 3.4 m.s^{-1} for Q = 110 L.s^{-1}), along with the Nature design (max mean magnitude of 2.5 m.s^{-1} for Q = 55 L.s^{-1}, and 2.7 m.s^{-1} for Q = 110 L.s^{-1}). As for the other RD, values of $\overline{U}$ were lower, registering overall max mean magnitudes of 2.2 m.s^{-1} for Q = 55 L.s^{-1}, and 2.5 m.s^{-1} for Q = 110 L.s^{-1}. Nevertheless, for configurations Large Boulders Aligned and Large Boulders Offset, 3D-contour maps showed localized zones of low-velocity (< 0.5 m.s^{-1}) between boulders.

Regarding $\bar{h}$ (Figure 2.4 and 2.5), mean depths varied according to Q and the RD tested. Higher depths were registered, as expected, with Q = 110 L.s^{-1} (> 4 cm, on average, except for the configuration Large Boulders Offset that registered a variation of 10 cm), and in the configurations with the larger boulders, especially in the Large Boulders Offset ($\bar{h}$ = 27 cm, for Q = 55 L.s^{-1}, and 37 cm, for Q = 110 L.s^{-1}). Shallower water depths were observed in the configurations Control ($\bar{h}$ = 6 cm, for Q = 55 L.s^{-1}, and 10 cm, for Q = 110 L.s^{-1}) and Nature ($\bar{h}$ = 9 cm, for Q = 55 L.s^{-1}, and 13 cm, for Q = 110 L.s^{-1}).

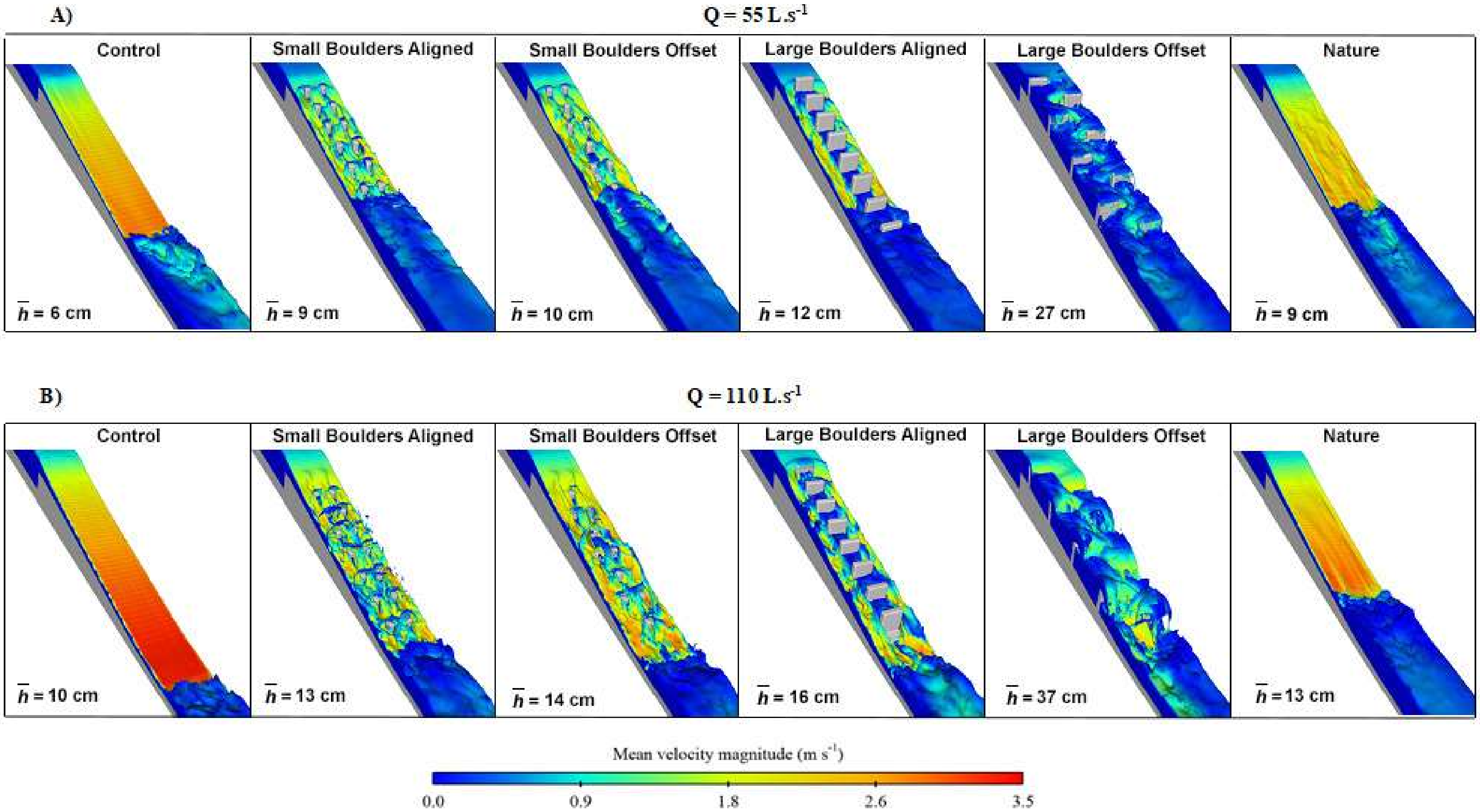

Fig. 0-4. Characterization of the mean water velocity magnitude ($\overline{\boldsymbol{U}} = (\overline{\boldsymbol{u}'^2} + \overline{\boldsymbol{v}'^2} + \overline{\boldsymbol{w}'^2})^{1/2}$; m.s^{-1}) for each configuration tested, using the computational fluid dynamics (CFD) commercial software FLOW-3D®, considering the discharges of: A) 55 L.s^{-1}, and B) 110 L.s^{-1}. Mean water depths over the ramp ($\overline{\boldsymbol{h}}$; cm) is also presented for each configuration.

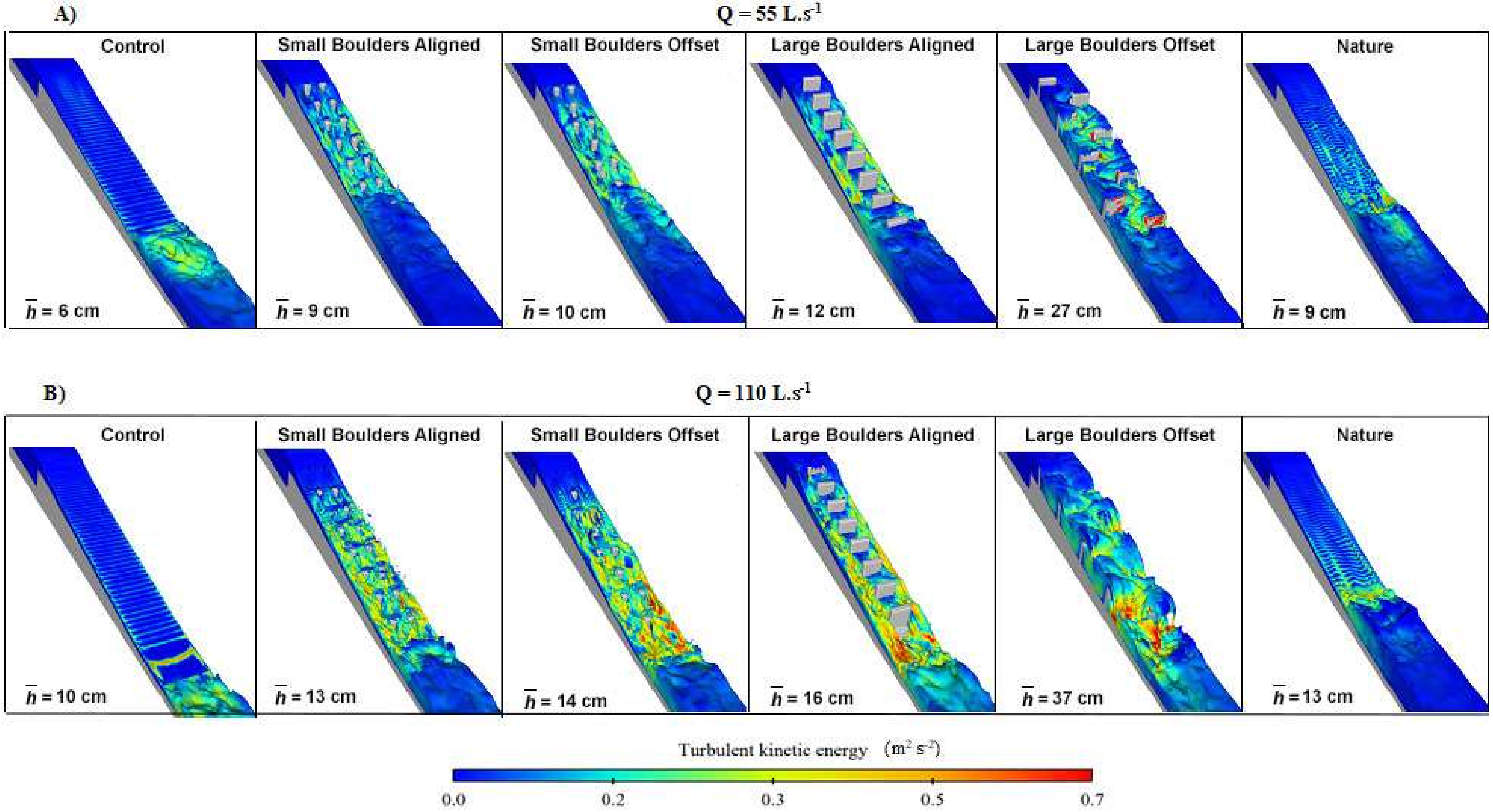

Fig. 0-5. Characterization of the turbulent kinetic energy per unit mass (TKE = $\frac{1}{2}\left(\overline{u'^2}+\overline{v'^2}+\overline{w'^2}\right)$; $m^2.s^{-2}$) for each configuration tested, using the computational fluid dynamics (CFD) commercial software FLOW-3D®, considering the discharges of: A) 55 $L.s^{-1}$, and B) 110 $L.s^{-1}$. Mean water depths over the ramp ($\overline{h}$; cm) is also presented for each configuration.

2.5. Discussion

The present study focused on the influence of RD and Q, as well as their interaction, on the passage performance of Iberian barbel negotiating low-head ramped weirs. The high number of observed movements (approaches, attempts to negotiate the ramp, and successful upstream passages) show that Iberian barbel were stimulated to move upstream and negotiate the ramped weirs. However, passage successes and efficiencies of designs varied among configurations tested, indicating that some substrates and spatial arrangements, along with discharge, provided more favourable hydrodynamic conditions for successful upstream passages of fish. Thus, to assess the effects of hydrodynamics on fish behaviour, numerical modelling (the 3D CFD model FLOW-3D®) was used in this study to characterize influential hydrodynamic variables, such as velocity magnitude, TKE, and water depths, present in each configuration tested, in order to identify areas of high velocity and turbulence gradients that might have affected fish movements. Over the last few years, 3D CFD models have proved to be a practical and robust tool to characterize hydrodynamics on several hydraulic structures, being widely used for the assessment of fish passages (e.g. studies on functioning over a wide range of discharges, prediction of suitable conditions for fish), optimization of designs, and evaluation of different retrofitting solutions (Heimerl et al. 2008; Feurich et al. 2012; Baki et al. 2016; Duguay et al. 2016; Kolden et al. 2016; Quaranta et al. 2017; Fuentes-Pérez et al. 2018; Quaresma et al. 2018; Quaranta et al. 2019; Sanagiotto et al. 2019). However, given that uncertainty in CFD modelling for Environmental Fluid Mechanics in complex flow fields, like the flow field in the vicinity of a macro-scale roughness (e.g., wake region), can arise from a very wide range of sources, care should be taken when performing a numerical model study (Blocken and Gualtieri 2012). In the present study, a careful verification and validation of the numerical model was done, to ensure that a substantial reduction in the uncertainty of the results was achieved, by carefully following CFD best practice guidelines (Blocken and Gualtieri 2012).

Like in other studies (Amaral et al. 2016; Muraoka et al. 2017; Amaral et al. 2018; Plesiński et al. 2018), Q, associated with velocity magnitude and turbulence, proved to be an important variable on the negotiation of the experimental low-head ramped weirs. In general, more approaches and attempts were registered with the lowest Q tested (55 L.s^{-1}), which had almost seven times more records when compared to Q = 110 L.s^{-1}. Nevertheless, for both Q, it was observed that, of the total number of fish approaches, only less than half resulted in effective attempts to negotiate the ramped weir, suggesting that many non-oriented Ap occurred, especially with 55 L.s^{-1}. Consequently, lower values of AE (%) were registered with 55 L.s^{-1}, as initially envisaged, except for the Nature design that achieved the highest value (75%). These results generally agree with previous studies on negotiation of low-head obstacles (e.g. Amaral et al. 2016; Goerig and Castro-Santos 2017; Amaral et al. 2018), and may indicate that, except for the Nature design, velocity magnitude (0.5–1.0 m.s^{-1}) and TKE per unit mass (0.2–0.3 m^2.s^{-2}) occurring close to the ramps, which are parameters directly related with Q and influenced by RD (Baudoin et al. 2014; Towler et al. 2015), were not the most suitable to create attractive paths for fish to attempt to negotiate the obstacle and successfully pass it (Pavlov et al. 2000; Elder and Coombs 2015; Katopodis et al. 2019).

In addition to hydrodynamics though, biological factors beyond swimming ability may affect attraction and passage efficiency, as the following field assessment indicates. Landsman et al. (2018) evaluated a nature-like fishway, for passage of Rainbow Smelt (*Osmerus mordax*) and Brook Trout (*Salvelinus fontinalis*). In each of the two study years, AE at the fishway for Rainbow Smelt was almost the same, 30.1% (2014; mean TL=17 cm, range 15–24 cm) and 30.4% (2016; Mean TL=15.9 cm, range 14–26 cm), while PE was 26.5% and 28.6%, respectively (not significantly different). In contrast, although AE for Brook Trout was only 9.2% in 2016 (Mean TL= 28.1 cm, range 16–52 cm), PE was 91.7%. The rather low but close AE and PE values for the shorter Rainbow Smelt, compared to the very high PE, despite the very low AE for the longer Brook Trout, implies that biological factors beyond length and corresponding swimming performance may contribute to successful passage effectiveness. Moreover, as Plesiński et al. (2019) mentions, although for successful upstream passages fish may only need one usable path, for approaching the obstacle accurately and successfully attempt to negotiate it, fish primarily need to be able to detect the most functional paths when confronted with varied hydrodynamic conditions. Thus, metrics of attraction such as AE, which are directly dependent on the movements of Ap and At, vary substantially depending on the type of obstacle, its design and specificities (e.g. different retrofitting solutions, as tested in this study), and the consequently surrounding hydrodynamic conditions (Bunt et al. 1999; Calles and Greenberg 2009; Baudoin et al. 2014; Bunt et al. 2016). Therefore, future studies should focus on the quantification of the attraction in further subcomponents (Roscoe and Hinch 2010), such as: guidance (i.e. arrival at the entrance) in response to hydrodynamic cues, and entry (i.e. decision to enter), using, for example, biotelemetry techniques to monitor fine-scale behaviour (Cooke et al. 2004; Cooke and Hinch 2013).

Regarding S, as initially expected, the number of successes decreased with the increase of Q, except for the two RD using small boulders (Small Boulders Aligned and Small Boulders Offset). However, in terms of PE, higher values were unexpectedly achieved in all the configurations with Q = 110 $L.s^{-1}$. Nevertheless, in both Q tested, configurations Small Boulders Aligned and Small Boulders Offset registered the lowest values of PE (0% for both configurations with 55 $L.s^{-1}$; 9 and 11% with 110 $L.s^{-1}$). In these two configurations, high values of velocity (2.0–3.0 $m.s^{-1}$) and TKE per unit mass (0.3–0.5 $m^2.s^{-2}$) were registered and, especially, unpredictable fluctuations in both hydraulic parameters occurred along the ramp and at its toe, as showed in the CFD 3D-contour maps (Figures 2.4 and 2.5). These conditions, together with the chaotic and small water depths over the ramp (ranging from 7–8 cm and 13–14 cm, for 55 $L.s^{-1}$ and 110 $L.s^{-1}$, respectively), may have influenced fish passage because, as mentioned by Liao (2007), Elder and Coombs (2015) and Plesiński et al. (2018), fish tend to avoid unexpected fluctuations of velocity, chaotic flows, and other flow conditions that may interfere with their swimming trajectories (e.g. vortex systems with diameters similar or greater than the fish body length; Silva et al. 2012). Moreover, the size of the boulders used in these configurations (7.5 cm long × 7.5 cm wide × 15 cm high) may have been unsuitable to provide sizeable low-velocity zones, which could have been used by fish as resting areas, to recover energy and prepare for the successful upstream passage (Liao 2007; Muraoka et al. 2017; Plesiński et al. 2018; Wang and Chanson 2018; Knapp et al. 2019). As for the two configurations using larger boulders (25 cm long × 7.5 cm wide × 30 cm high), Large Boulders Aligned and Large Boulders Offset, CFD 3D-contour maps showed localized zones of low-velocity (< 0.5 m.s^{-1}) between boulders, which could have provided conditions for fish to shelter and rest, as observed during the trials. Nevertheless, despite the occurrence of lower velocities and higher water depths (12–16 cm with 55 L.s^{-1}, and 27–37 cm with 110 L.s^{-1}, for Large Boulders Aligned and Large Boulders Offset, respectively), these two configurations were also not the most successful. The high TKE per unit mass (above 0.4 m^{2}.s^{-2}) present along the ramp, and especially at its toe, resulting from the combination of RD and Q, should have been the main condition that hampered fish upstream movements. As referred by Knapp et al. (2019), although localized low-velocity areas displaying high turbulence may provide resting conditions for fish, in the upstream negotiation of obstacles this turbulence per se may be limiting on the fish swimming ability. Finally, concerning the best results, the configuration Nature was, overall, the best RD tested. Comparing with the Control configuration, velocity magnitudes along the ramp (Control: 2.6–3.4 m.s^{-1}, and Nature: 2.5–2.7 m.s^{-1}), and especially TKE per unit mass registered downstream (Control: < 0.3 m^{2}.s^{-2}, and Nature: < 0.25 m^{2}.s^{-2}), were lower for both Q tested. Therefore, the random placement of natural cobbles on ramped weirs, as in this study, may generate an effective energy dissipation, reducing velocity and turbulence along the ramp, and especially downstream (Baudoin et al. 2014; Bunt et al. 2016; Muraoka et al. 2017; Rodgers et al. 2017; Goodrich et al. 2018). Consequently, more suitable conditions for fish to approach and successfully negotiate ramped weirs may be promoted upon retrofitting these structures with natural cobble substrate, as it may provide important “flow refugia”, creating homogeneous areas, with reduced velocity and turbulence, that fish may use to rest during the upstream negotiation of the ramp (Johnsson et al., 2019). Future studies, contemplating distinct fish species with different ecological traits (e.g. small-bodied fish that utilize the upper portion of the water column), additional biological groups (e.g. macroinvertebrates), and a different range of discharges, should be considered to enhance the knowledge on species passage effectiveness. Improved biological and hydrodynamic conditions at low-head ramped weirs are needed to help engineers and biologists to design more holistic structures, or retrofitting solutions, for low-head instream obstacles.

2.6. Conclusions

This study highlighted the importance of RD and Q, and especially of hydrodynamics resulting from the combination of these two factors, on the passage performance of the Iberian barbel, a medium-sized potamodromous cyprinid, negotiating low-head ramped weirs. The fact that experiments were carried out under laboratory conditions allowed the detailed observation of fish behaviour (e.g. fish approaching the ramp, attempts to pass, successful upstream passages), as well as the control and the analysis of all the physical and hydraulic factors (e.g. substrate arrangements, discharges) considered preponderant in the successful passage of fish. Moreover, by using the 3D CFD model FLOW-3D® to characterize the hydrodynamics in each configuration tested, it was possible to identify areas of high velocity and turbulence gradients that might have affected fish movements.

Overall, results showed that the type of substrate, especially the size and the spatial arrangement selected to retrofit this type of low-head obstacles, together with discharge, played an important role in the creation of suitable hydrodynamics for the upstream successful negotiation of ramped weirs. As observed in other studies (Branco et al. 2013; Santos et al. 2014; Muraoka et al. 2017; Rodgers et al. 2017; Goodrich et al. 2018; Landsman et al. 2018; Johnson et al. 2019), the use of natural substrate may help to increase the permeability of these structures to fish movements, by providing an effective energy dissipation along the obstacle. That energy dissipation, together with the occurrence of low-velocity areas and small turbulence intensities, and the essential prevalence of spatial and temporal predictable flows, have proved to be key factors to consider in planning these type of retrofitting solutions (Baudoin et al. 2014; Goodrich et al. 2018; Plesiński et al. 2018; Knapp et al. 2019). Moreover, as mentioned by Katopodis et al. (2019) and Knapp et al. (2019), in addition to hydrodynamics, it is also crucial to analyse fish swimming behaviour and passage performance in order to establish more applicable design guidelines. Thus, the outcomes from the present work, complemented with further research on hydrodynamics of low-head ramped weirs and fish passage performance, engaging laboratory experiments and in-situ studies (Ovidio et al. 2007), may significantly contribute to help engineers and biologists to design more appropriate passage structures for low-head instream obstacles.

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V. General discussion

The main goal of this thesis was to investigate the effects of small weirs, particularly small broad-crested weirs and low-head ramped weirs, which are the most frequently found in Iberian watercourses, on passage performance of Iberian potamodromous cyprinids. Thus, fish behaviour and passage performance negotiating those small obstacles were studied in order to increase the knowledge on potamodromous cyprinids, which are often less considered, for dealing with problems of existing small weirs and suggest different designs that may improve the permeability of those small barriers for these species. Iberian barbel was selected as target species, representing the medium-sized benthic potamodromous cyprinids that inhabit Iberian and Western European rivers. This kind of approach, which uses a representative of a group of organisms that are independent of taxonomic restrictions but explore the same set of resources, such as similar ecological guilds in terms of physical habitat (benthic), reproduction strategy (lithophilic), and migratory behaviour (potamodromous), has been supported by several authors (e.g. Fauth et al. 1996; Leonard and Orth 1988; Branco et al. 2013a).

In addition to the study performed in the field, presented in part II of this thesis, which was carried out in a 5.6 km-long upstream segment of the Alviela River, this thesis had a strong component of experiments performed in an indoor ecohydraulic channel, located at the Hydraulics and Environment Department of LNEC. In these laboratorial experiments, compiled in part III and IV, a small experimental broad-crested weir, adjustable for different plunge pool depths (D), waterfall heights (H), and weir crest widths (W), and an experimental low-head ramped weir, varying in length (L) and slope (S), and further retrofitted with different substrates (RD), were tested under different discharges (Q). The fact that these experiments were carried out under laboratory conditions allowed the control and analysis of all the physical and hydraulic parameters (e.g. plunge pool depth, waterfall height, weir crest width, ramp length, ramp slope, discharge), considered preponderant in the successful passage of Iberian barbel, as well as the full, and unobtrusive, observation of fish behaviour negotiating the experimental weirs (e.g. fish approaching the obstacle, attempts to pass, successful passages). Therefore, as mentioned by some authors (e.g. Kemp et al. 2006; Martin and Bateson 2007; Alexandre et al. 2013; Santos et al. 2014), in these laboratory studies, by manipulating the key variables/parameters, it is possible to control confounding effects that could bias the results, and the observed responses of fish will contribute to improve the understanding of events occurring in the wild.

In this final part of the thesis (part V), the main results and conclusions of all the experiments performed are summarized, considering the central issues: the influence of small weirs on migratory movements of Iberian barbel in the wild; the negotiation of small broad-crested weirs and low-head ramped weirs by medium-sized potamodromous cyprinids; the overall effect of discharge on passage performance of Iberian barbel; and some management recommendations based on the information gathered in these experiments. Moreover, final considerations, introducing some future research guidelines, are also presented in this part.

1. Key findings, contributions to scientific knowledge, and recommendations for management

The first study presented in this thesis, compiled in part II, aimed to assess the most common type of small weirs and understand how they affect, in an otherwise non-impacted upstream segment of a stream, the Alviela River, the movements of Iberian barbel, considering both fish displacements upstream or downstream of barriers, and fish maintenance between the same barriers throughout the study period (five sampling seasons, from spring 2012 to early summer 2013). During the study, the identified small weirs were seasonally characterized, considering the ICF – Index of River Connectivity (Solà et al. 2011), and fish sampled were marked using VIE tags, applying a fish-tagging code (combining three colours and four body locations) that allowed the identification of fish captured/recaptured by site and season. Results from this field assessment revealed that evaluated barriers – broad-crested and low-head ramped weirs, were mostly insurmountable (ICF results - Bad) during the main reproductive season of Iberian barbel, which occur mostly during late spring–early summer (Lucas and Baras 2001; Santos et al. 2005; Baudoin et al. 2014). However, with the increase of discharge, following the natural hydrological cycle (late autumn–winter), an increase of barrier permeability (ICF results – Poor to Moderate) was also registered. Regarding fish movements, despite this unfavourable barrier permeability, a portion of the barbel population (11%) was able to move between river segments, negotiating the weirs in both upstream and downstream directions. Nevertheless, although barbel were able to negotiate these small weirs, they apparently prefer not to move, remaining between barriers especially when adequate spawning grounds are present. Therefore, attending to physical and hydrodynamic conditions (e.g. characteristics of the weir, discharge), these small barriers may introduce a resistance to migratory movements, and so, some fish may cease to migrate, changing their life strategy to become resident. Thus, an artificial selection of behavioural phenotypes that favour residency may occur, inducing a population adaptation to the presence of small barriers (Knaepkens et al. 2005). This behaviour, called "partial migration" (Chapman et al. 2012), which was also observed in a similar species, *Barbus barbus* (Peňáz et al. 2002; Vilizzi et al. 2006), may be significant to the resilience of freshwater fish populations, augmenting their fitness (Smithson and Johnston 1999, Larson et al. 2002, Knaepkens et al. 2005), particularly under current conditions of intense river fragmentation and severe impacts on hydrology due to global changes.

The studies performed in the indoor ecohydraulic channel, using the small experimental broad-crested weir (part III) and the low-head ramped weirs (part IV), aimed to understand the influence of key hydraulic parameters – plunge pool depth, waterfall height, weir crest width, in the case of broad-crested weirs, and ramp length and slope, for low-head ramped weirs, on passage performance by Iberian barbel, across a range of different discharges. Throughout these laboratory experiments, where each tested configuration had 4 replicates, and each replicate lasted for a maximum of 60 minutes, fish movements (the number of times fish approach the obstacle, the number of attempts to pass, the number of successful upstream passages, and downstream passages) and behaviour (passage by swimming or jumping, in the case of broad-crested weirs) were registered, and metrics of passage performance, such as percentages of attraction efficiency and passage efficiency, were calculated.

Results from the experiments performed with the small broad-crested weirs demonstrated that, as in other studies (Kondratieff and Myrick 2005; Brandt et al. 2005; Kondratieff and Myrick 2006; Ficke et al. 2011), the combination of shallow plunge pool depths with high waterfall heights may inhibit the successful upstream passage of Iberian barbel. However, some results were different from those previously expected, as some of the combinations that might have been predicted to be easily negotiated by fish, such as the combination of higher plunge pool depths with lower waterfall heights, turned out to be less attractive, leading to a lower success of passage. Moreover, the type of passage behaviour adopted by Iberian barbel to upstream negotiate the experimental weir, by swimming or jumping, was highly dependent from the combinations of plunge pool depths and waterfall heights tested, and consequently from turbulence experienced downstream of the weir (Pasternack et al. 2006; Baudoin et al. 2014). Iberian barbel negotiated most configurations by swimming through the water nappe formed in the downstream face of the experimental broad-crested weir but, as the waterfall height increased, fish were able to switch their behaviour, jumping more times to successfully pass the obstacle. Since potamodromous cyprinids are considered by some authors as a “non-jumping species” (Baudoin et al., 2014; Doadrio et al., 2011), this was an expected result. Nevertheless, as mentioned by Baudoin et al. (2014) and Morán-López and Tolosa (2017), although jumping is not the passage behaviour most frequently used by these species to negotiate obstacles, when confronted with higher barriers to overcome, or high turbulence, most cyprinids are able to modify their individual passage behaviour increasing their attempts to pass by jumping, and being sometimes successful in passing by this means. As for the influence of the weir crest width, contrarily to what was initially expected, increasing widths did not restrict the upstream/downstream movements across the weir. In fact, for downstream movements, narrow crest widths may have constrained fish movements, possibly due to velocity gradients observed on such short space and being too strong to encourage downstream passages (Williams et al. 2012). Considering the upstream negotiation, Iberian barbel was able to swim along all tested widths, withstanding unfavourable hydraulic conditions such as shallow water depth over the weir crest (≈ 0.03 m), or high-water velocities (e.g. ≈ 2 m.s^{-1}).

Concerning the experiments using the low-head ramped weirs, results suggest that both parameters tested, ramp length and slope, had a marginally significant influence on the successful negotiation. As concluded by Goerig and Castro-Santos (2017), and observed in the previous experiments with the broad-crested weir, the "fish passage paradox", concerning the influence of water velocity and, consequently, of turbulence and energy dissipation present on these small barriers (Pasternack et al. 2006; Baudoin et al. 2014) in the attraction of fish and on the successful negotiation of the obstacle, was also observed in these experiments. Values of attraction efficiency increased with increasing ramp length and slope, where higher values of water velocity (> 3 m.s^{-1}) were registered downstream, whereas the number of successful upstream passages, and consequently passage efficiency, decreased upon increasing ramp length. Regarding the ramp slope, it was found that successful upstream passages, and thus passage efficiency, peaked at the intermediate level (in this case, 20%), in which intermediate values of water velocity, and potential turbulence associated, occurred.

Therefore, fish were attracted to the ramped weir by high values of water velocity but, at the same time, it might have been a limiting factor for successful upstream passage – so, what attracts fish is what may hamper their movements.

The addition of natural substrates, like cobbles or boulders that were tested in this thesis, is frequently used as retrofitting solution (Branco et al. 2013b; Santos et al. 2013; Baudoin et al. 2014; Santos et al. 2014; Muraoka et al. 2017; Rodgers et al. 2017; Goodrich et al. 2018; Landsman et al. 2018; Plesiński et al. 2018; Wang and Chanson 2018; Johnson et al. 2019) to enhance fish passability. The placement of these substrates along the sloped face of low-head ramped weirs increases bed roughness, and consequently promote energy dissipation, creating localized zones of low-velocity and low-turbulence (Towler et al. 2015; Muraoka et al. 2017; Rodgers et al. 2017; Plesiński et al. 2018) that may be used by fish as resting areas during the upstream negotiation of ramps (Liao 2007; Elder and Coombs 2015; Landsman et al. 2018; Wang and Chanson 2018; Knapp et al. 2019). For potamodromous cyprinids, that are considered as species of weaker swimming capabilities, these low-velocity and low-turbulence zones may be particularly important (Santos et al. 2013; Baudoin et al. 2014; Santos et al. 2014) for the complete negotiation of ramped weirs, as observed during the experiments. Results indicated that the type of substrate, mainly the size (in this case, the cobbles used in the Nature configuration were 10 to 30 cm; small boulders were 7.5 cm long × 7.5 cm wide × 15 cm high; large boulders were 25 cm long × 7.5 cm wide × 30 cm high), and its spatial arrangement (cobbles were randomly distributed along the ramp; boulders were spatially aligned and alternated) are important factors in the creation of suitable hydrodynamics (e.g. areas of low-velocity and small turbulence intensities, prevalence of spatial and temporal predictable flows) for the upstream successful negotiation of ramped weirs (Baudoin et al. 2014; Goodrich et al. 2018; Plesiński et al. 2018; Knapp et al. 2019) by Iberian barbel. The configurations using small boulders (Small Boulders Aligned and Small Boulders Offset) were the least efficient in terms of passage, recording the lowest values of successful passages and, consequently, passage efficiency. In these two configurations, high values of velocity (2.0–3.0 $m.s^{-1}$) and turbulent kinetic energy (0.3–0.5 $m^2.s^{-2}$) were displayed and, especially, unpredictable fluctuations in both hydraulic parameters occurred along the ramp and at its toe, conditions that might have hampered the fish upstream movements. On the other hand, the Nature configuration was, overall, the best design tested, registering the higher number of successful upstream passages, and consequently of passage efficiency, and also higher values of attraction efficiency (except for discharge of 110 $L.s^{-1}$). When compared to the Control configuration (ramp without substrates), the cobbles used in the Nature configuration provided an effective energy dissipation along the ramp, reducing velocity (Control: 2.6–3.4 $m.s^{-1}$, and Nature: 2.5–2.7 $m.s^{-1}$) and turbulence (Control: < 0.3 $m^2.s^{-2}$, and Nature: < 0.25 $m^2.s^{-2}$), especially downstream. Therefore, the random placement of natural cobbles on ramped weirs, as tested in this study, may help to increase the permeability of ramped weirs to fish movements, by providing more suitable conditions for fish to approach and successfully negotiate the obstacle.

Discharge was one of the hydraulic parameters common to all studies developed in this thesis. Closely linked to water column over the obstacle, and also with water velocity and turbulence (Pasternack et al. 2006; Baudoin et al. 2014; Towler et al. 2015), discharge proved to be a preponderant parameter on both the attraction of fish and on successful negotiation of the obstacles throughout all experiments. In the field, the study presented suggest that the impact of small weirs on potamodromous cyprinids movements increased during low-flow periods. Values of ICF – Index of River Connectivity were less favourable during the spring–summer period, when a decrease of discharge commonly occur, and so, a reduction on the passability of these barriers may be expected along those months, due to shallow water columns over the obstacles. Moreover, as mentioned before, the combination of small barriers, that are highly present in almost all watercourses (Nilsson et al. 2005; Ordeix et al. 2011; King et al. 2017), and reduced river flows will negatively affect longitudinal connectivity, exposing the ability of aquatic ecosystems, and especially fish populations, to deal with habitat modification/degradation and future events of flow alteration. Results from the laboratory experiments also highlight the effect that discharge had on the negotiation of these small barriers, both in broad-crested weirs and low-head ramped weirs. In general, it was observed that the number of successful passages, as well as fish approaches and attempts to pass the weir, mainly decreased with increasing discharge, and so, with increasing water velocity and potential turbulence. Additionally, in the presence of high discharges, fish also tended to require more time to successfully negotiate the weir. However, considering the metrics of passage performance, higher percentages of attraction efficiency were in general achieved with higher discharges tested (in this case, ≈ 50 % for the tested 100 $L.s^{-1}$ and 110 $L.s^{-1}$), whereas for passage efficiency, correspondent percentages were usually low (≈ 22 %) with increasing flows. These results corroborate the concept of the "fish passage paradox" (Goerig and Castro-Santos 2017), previously mentioned, regarding the influence of discharge in the negotiation of obstacles – in these experiments, discharge had a positive influence on the attraction of fish to the obstacle but, at the same time, it might have been a limiting parameter for the successful upstream passage. Even for downstream passages over broad-crested weirs, it was observed that high discharges reduced the number of movements, fact that may be explained by the natural behaviour of fish to avoid areas with high water velocity, unexpected flow fluctuations, and turbulence (Liao 2007; Elder and Coombs 2015; Silva et al. 2016) like those that should occur in the vicinity of these structures. Nevertheless, contrary to what was initially expected, the highest number of successful passages, and consequently of passage efficiency, were not registered in configurations that tested the lowest discharge, or that displayed low water velocities (<< 1 $m.s^{-1}$) and turbulence (TKE << 0.15 $m^2.s^{-2}$), such in the trials that tested 25 $L.s^{-1}$, in the case of small broad-crested weir, or that tested a 10 % slope, for low-head ramped weir. This fact may indicate that these velocity magnitudes and turbulence intensities were not the most suitable to create attractive paths for fish to attempt to negotiate the obstacle and successfully pass it (Powers and Orsborn 1985; Pavlov et al. 2000; Elder and Coombs 2015; Katopodis et al. 2019). Therefore, tested configurations that displayed intermediate values of water velocity and turbulence were the most successful, registering higher number of upstream successful passages, as well as high percentage of passage efficiency.

Overall, results of these experiments highlight the complexity and importance of the interaction of all key hydraulic parameters tested, as well as fish swimming and jumping abilities, to achieve successful negotiation of these small barriers. All the unfavourable conditions experienced throughout these experiments (e.g. shallow plunge pool depths, high waterfall heights, low/high discharges, high water velocity and turbulence, predictable/chaotic flows) commonly occur in nature. The combination of these conditions may lead to an increase in energy expenditures of fish during negotiation of the obstacles (Enders et al. 2005; Tritico and Cotel 2010; Wilkes et al. 2017) that may then reduce swimming performance and possibly cause disorientation (Pavlov et al. 2000; Liao 2007; Tritico and Cotel 2010) and fish fatigue (Katopodis and Gervais 2012). Concomitantly, a delay on fish migration and/or a reduction on the number of fish that access important upstream habitats for spawning may occur (in addition to other adverse effects; e.g. Ovidio and Philippart 2002; Castro-Santos and Haro 2003; Kemp and O'Hanley 2010; McLaughlin et al. 2013). Therefore, based on the results gathered in this thesis, some recommendations for the management of these small obstacles, in order to address their adverse impacts on fish movements, may be highlighted, as follows:

- for broad-crested weirs, low ratios of plunge pool depth/waterfall height may inhibit the successful passage of fish; however, the application of high ratios may not necessarily be the most successful design, due to complex hydrodynamics associated to these structures and its interaction with fish behaviour. Therefore, the definition of thresholds for these key-parameters should be determined considering not only the value of ratios, but also the nominal values of each parameter. Moreover, the swimming and jumping performance of target species should also be taken into account when designing these small obstacles.
- for low-head ramped weirs, designs with low slopes may not necessarily be the best option, because they are less attractive for the fish and their length is higher, thereby increasing constructions costs. Therefore, higher slopes, although not excessive, could be more attractive for fish, less space-demanding, and probably more cost-effective. Furthermore, the swimming capability of fish should also be considered when determining design thresholds for water velocity and turbulence, both over the ramp and downstream.
- the addition of natural substrates, such as cobbles or large boulders, can be an effective retrofitting measure to increase the permeability of these structures to fish movements. The size and the spatial arrangement of substrates should be carefully planned in order to provide, together with energy dissipation, the occurrence of low-velocity areas and small turbulence intensities, which may be used by fish as resting areas, and that was shown to be important in the approach of fish to the obstacle and on its successful negotiation. Additionally, as recommended before, fish swimming behaviour and passage performance should also be considered to establish suitable hydraulically designs.
- to improve passability for potamodromous cyprinids, like Iberian barbel, results from the experiments presented in this thesis suggest that values of water velocity and turbulence, registered downstream and over the obstacle, should be, generally, lower than 3 $m.s^{-1}$ and 0.3 $m^2.s^{-2}$, respectively. However, to enhance fish attractiveness, velocity magnitude and turbulent kinetic energy nearby these structures should not have values much lower than 1 $m.s^{-1}$ and 0.1 $m^2.s^{-2}$, respectively. Nevertheless, further studies must be made to better understand the thresholds, and the complexity inherent to the negotiation of these small weirs, encompassing hydrodynamics, both upstream and downstream, as well as behaviour and physiological conditions of fish.

2. Future research

Considering the findings and the limits of this work, more research should be made, bringing together more in-situ studies with laboratory experiments, to better understand the effective impact of small instream obstacles on migratory movements of fish. Therefore:

- more field studies should be conducted, employing other tracking techniques, such as radio-telemetry and EMG-telemetry, to further understand, and discriminate, standard cyclic movements and true migrations. Furthermore, the influence those small barriers, and the additional impacts of hydrological changes, may have on migratory movements and fish physiological conditions should be further assessed, combining these tracking techniques with specific fish morphological/physiological indices;

- further experiments, considering distinct fish species with different ecological traits (e.g. small-bodied fish that utilises the upper portion of the water column), different designs of small weirs, and a different range of discharges, should be performed to enhance the knowledge on species passage performance, and on hydrodynamics of small instream obstacles, to help engineers and biologists to design more holistic structures;

- experiments with non-native species (e.g. roach *Rutilus rutilus*, bleak *Alburnus alburnus*, European perch *Perca fluviatilis*), combining in-situ and laboratory studies, should also be considered, to investigate the possibility of these obstacles acting as selective barriers to the dispersal of these species, and also to quantify their real effectiveness in this dispersal control.

- future studies should consider the quantification of further attraction factors, such as the guidance (i.e. arrival at the structure) in response to hydrodynamic cues, and the passage (i.e. decision to negotiate the structure), using biotelemetry techniques to monitor fine-scale behaviour and better understand the influence of macro- and micro-hydrodynamic complex conditions on passage performance.

3. Conclusion

River fragmentation by hydraulic infrastructures has been pointed out as one of the most serious threats to the sustainability of fish populations (Aarts et al. 2003; Nilsson et al. 2005; Calles and Greenberg 2009; Reid et al. 2019). Although far more numerous than dams (Lucas et al. 2009), the impact of small weirs (< 5 m in height; ONEMA 2010; Solà et al. 2011) on fish movements have received much less attention. However, recent studies have considered that, due to their abundance (2–4 orders of magnitude more numerous than dams; Lucas et al. 2009), their cumulative impact on fish populations may be greater than estimated (Baudoin et al. 2014; Branco et al. 2017; Birnie-Gauvin et al. 2019). Portuguese rivers have more than 8000 small weirs (Ordeix et al. 2018). Small broad-crested weirs, designed with a vertical downstream face, and low-head ramped weirs, which have inclined faces that do not generate a waterfall, are the most frequent types of small instream obstacles to fish movements (Solà et al. 2011; Branco et al. 2017). In this thesis, the negotiation of broad-crested and low-head ramped weirs by Iberian barbel, a medium-sized potamodromous cyprinid, was studied, considering the influence of key hydraulic parameters (plunge pool depth, waterfall height, weir crest width, in the case of broad-crested weirs; ramp length and slope, for low-head ramped weirs; and discharge) on passage performance of fish.

Experiments provided valuable insights to better understand how Iberian barbel respond to macro- and micro-hydrodynamic complex conditions that occur downstream, as well as over, barriers – what attracts them and what repels them. Nevertheless, the parameters tested in the laboratory, and their interactions, do not fully explained all the complex situations that fish can encounter in nature (e.g. temperature, noise, substrate roughness, weir geometry irregularities, channel complexity, cover, etc.). Moreover, because not all size classes of fish were tested, due to the burden that these experiments would represent (time, number of fish, laboratory conditions), different behaviours and abilities may be expected in experiments, and in the field, when using other size classes. Furthermore, although some authors refer to potamodromous cyprinids as “weaker swimmers” when compared to salmonids (Alexandre et al. 2013; Katopodis and Gervais 2016), the high swimming performance recorded in these experiments reveal that Iberian barbel can overcome conditions of water velocities and turbulence comparable to those surpassed by some salmonids of similar size (Mateus et al. 2008; Sanz-Ronda et al. 2016; Katopodis and Gervais 2016). Besides that high swimming capability, barbel also demonstrated the ability to swim along shallow waters (< 10 cm), and to jump to overcome obstacles, although this species is normally consider as “non-jumping” (Baudoin et al. 2014).

Overall, the outcomes from all studies compiled in this thesis are expected to be useful to identify potential migration obstacles for medium-sized potamodromous cyprinids and to define design criteria for the requalification of these small weirs, both broad-crested and low-head ramped weirs, improving the permeability of barriers and fish passage, and consequently habitat connectivity, and population management. Nevertheless, further studies are needed to better understand the effect that barriers, and the additional impacts of hydrological changes, may have on migratory movements and on fish physiological conditions, considering distinct fish species, with different ecological traits, and considering the assessment of other important factors of fish passage performance, such as the quantification of the attraction in further subcomponents (e.g. guidance, and effective passage).

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