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ECOHYDRAULICS OF POOL-TYPE FISHWAYS FOR THE IBERIAN BARBEL (*LUCIOBARBUS BOCAGEI*, STEINDACHNER, 1865)

“DOCUMENTO PROVISÓRIO”

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minha mãe Maria Teresa e de minha avó Maria Virgínia

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RESUMO

"Ecohidráulica de passagens para peixes por bacias sucessivas para o barbo Ibérico (*Luciobarbus bocagei*, Steindachner, 1865)"

Este estudo analisa o impacto de diferentes condições hidráulicas na movimentação para montante do barbo Ibérico em passagens para peixes (PPP) por bacias sucessivas. Desenvolvido num protótipo experimental de PPP por bacias sucessivas e incluindo peixes de diferente dimensões, o estudo investiga: i) a eficiência de passagem por orifícios submersos ou descarregadores de superfície; ii) o efeito da velocidade, turbulência e tensões de Reynolds, no comportamento desta espécie; iii) a adequabilidade de orifícios desalinhados e alinhados para a passagem dos peixes e, finalmente, iv) a eficiência de orifícios desalinhados e alinhados com uma barra deflectora à movimentação dos espécimes. A PPP por bacias sucessivas demonstrou ser eficiente para a passagem a montante desta espécie. Os espécimes utilizaram preferencialmente os orifícios de fundo, principalmente os peixes de menores dimensões que apesar da sua maior capacidade reostáctica, apresentaram grandes dificuldades em transpor a passagem. O seu comportamento foi também o mais afectado pela turbulência e tensões de Reynolds, que se destacaram como principais variáveis a afectar o movimento dos peixes. O alinhamento dos orifícios demonstrou não ser adequado para a passagem dos peixes, mesmo com a introdução de uma barra deflectora. Os resultados são discutidos em termos de futuros delineamento de investigação.

Palavras-chave: barbo Ibérico, migração, passagem para peixes por bacias sucessivas, velocidade, turbulência, tensões de Reynolds

ABSTRACT

This study analyses the impact of different hydraulic conditions on the Iberian barbel's upstream movements in a pool-type fishway. Developed in an experiment pool-type fishway prototype and including fish of different sizes, this study investigates: i) the efficiency of passage through submerged orifices or notches; ii) the effect of velocity, turbulence and Reynolds shear stress on this species' behaviour; iii) the suitability of straight and offset orifices to fish's passage and, finally, iv) the efficiency of offset and straight orifices with a deflector bar for this specimens' movements. The fishways was found to be efficient to the upstream passage of this species. Submerged orifices were preferentially used by specimens, mainly by small fish which, although their higher rheostatic capacity, showed strong difficulties to pass trough the fishway. The behaviour of the latter was also the most affected by turbulence and Reynolds shear stress, which seemed to be the variables affecting fish' movements the most. Straight orifices wer found not be adequate to fish passage, even when added of a deflector bar. The results are discussed in terms of future research delineation.

Key words: Iberian barbel, migration, pool-type fishways, velocity, turbulence, Reynolds shear stress

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A = área de secção transversal do peixe;
A_o = área do orifício de fundo;
B = largura da bacia;
b_o = largura do orificio;
C_D = coeficiente de arrasto;
$D.$ = Comprimento da trajectória;
$Dist$ = distância percorrida pelo peixe;
f = frequência de ondulação do peixe;
F_D = força na direcção do escoamento;
g = aceleração da gravidade;
h = profundidade da água;
h_m = profundidade media daágua numa bacia ;
K = energia cinética da turbulência;
K_c = energia cinética da turbulência média numa célula;
$K_{max.}$ = energia cinética da turbulência máxima;
K_{mean} = energia cinética da turbulência média;
$K_{min}.$ = energia cinética da turbulência minima;
L = Cumprimento da bacia;
l = comprimento do peixe;
P_v = potência volumétrica dissipada;
Q = caudal de descarga;
t = tempo;
TI = intensidade de turbulência;
TI_c = intensidade de turbulência média numa célula;
$TI_{max}.$ = intensidade de turbulência máxima;
TI_{mean} = intensidade de turbulência média;

TI_{min} = intensidade de turbulência minima;

TL = comprimento total do peixe;

t_{min} = tempo mínimo entre duas contracções musculares;

U = velocidade resultante sobre o peixe;

u, v, w = Components da velocidade num ponto em x, y e z;

u', v', w' = fluctuações das velocidades em x, y, e z;

u'_{rms}, v'_{rms}, w'_{rms} = raiz quadrada de u, v, w;

U_c = velocidade média na célula;

V = velocidade do escoamento;

V(t) = velocidade instantânea num certo ponto;

$V(t)$ = velocidade instantanea num ponto;

$V_{cr.}$ = velocidade de cruzeiro;

$V_{max\ nat}$ = velocidade máxima de natação;

$V_{max.}$ = velocidades máximas;

V_{mean} = velocidades médias;

$V_{min.}$ = velocidades minimas;

V_o = velocidade do escoamento maxima no orificio;

V_{peixe} = velocidade do peixe;

V_{xym}, V_{xzm}, V_{yzm} = velocidade máxima nos planos xy, xz e yz;

$V'(t)$ = fluctuação da velocidade no instante t

$\overline{V}$ = velocidade media do escoamento;

x, y, z = coordenadas;

xv , ,yv e ,zv = componentes tridimensionais;

Δh = diferença do nível de água entre duas bacias;

κ = energia cinética da turbulência adimensional;

$\overline{(-\rho u'v')}_m$ = medias máximas das tensões de Reynolds no plano horizontal XY;

$-\rho\overline{u'v'}_{max}$ = tensões de Reynolds máximas;

$-\rho\overline{u'v'}_{mean}$ = tensões de Reynolds médias;

$-\rho\overline{u'v'}_{min}$ = tensões de Reynolds minimas;

ρ = densidade da água;

$-\rho\overline{u'v'}_{c}$, $-\rho\overline{u'w'}_{c}$, $-\rho\overline{v'w'}_{c}$ = tensões de Reynolds médias nas células, para as components xy, xz e yz.

$\overline{(-u'v')}_{m}$, $\overline{(-u'w')}_{m}$, $\overline{(-v'w')}_{m}$ = médias máximas das tensões de Reynolds nos planos xy, xz e yz;

1. INTRODUÇÃO

1.1. O FENÓMENO DA MIGRAÇÃO

As comunidades piscícolas são extremamente dependentes das características do habitat do meio aquático, suporte de todas as suas funções biológicas tais como a reprodução, a alimentação e locomoção (Lucas e Baras, 2001; Porcher e Travade, 2002). O fenómeno da migração, característico de grande parte das espécies piscícolas, emerge como resultado da separação temporal e espacial dos recursos vitais ao desenvolvimento das espécies ao longo do seus ciclos de vidas (Northcote, 1998). Este processo é por conseguinte extremamente importante para a manutenção das populações piscícolas (Porcher e Travade, 2002)

De acordo com o seu tipo de funcionalidade, os habitats aquáticos podem então ser divididos em três tipos (Northcote, 1978, 1984): zonas de reprodução, zonas de alimentação e, quando as condições do meio se tornam desfavoráveis, zonas de refúgio; sendo a utilização dos mesmos, variável de acordo com as exigências inerentes às diferentes fases do ciclo de vida das populações piscícolas. As deslocações efectuadas com estes propósitos dão origem às designadas migrações reprodutivas, alimentares e de refúgio. Estas migrações envolvem geramente uma alternância cíclica entre dois ou três habitats, abrangendo uma larga fracção da população (Smith, 1985). Dependendo da natureza da migração e da espécie, a grandeza das distâncias percorridas pode variar entre poucos metros e distâncias consideravelmente significativas, na ordem dos milhares de quilómetros (Northcote, 1978; 1984). Um dos factores determinantes da amplitude das migrações é a capacidade das espécies em utilizarem habitats de diferentes salinidades durante o seu ciclo de vida (Lucas e Baras, 2001). Deste modo, podem ser definidos dois tipos de ciclo de vida, em função das espécies passarem toda a sua vida no mar ou água doce (ciclo de vida holobiótico) ou efectuarem deslocações entre ambientes com diferentes teores de salinidade (ciclo de vida anfibiótico). De acordo com a sua capacidade de adaptação a biomas com diferentes níveis de salinidade, as espécies piscícolas podem ser classificadas como: (a) espécies oceanódromas, cujas migrações ocorrem exclusivamente no mar; (b) espécies potamódromas, cujas migrações ocorrem exclusivamente em água doce; e (c) espécies diádromas, cujas migrações ocorrem entre o mar e água doce (Gresswell, 1997; Northcote, 1997). Os últimos podem ainda ser divididos em três classes de acordo com a direcção da migração e com a obrigatoriedade de adaptação dos diferentes estados de desenvolvimento a mudanças de salinidade (McDowall, 1997):

(i) Espécies anádromas, cujo crescimento e alimentação ocorrem no mar, dando-se posteriormente a migração dos adultos para água doce, com vista à reprodução, caracterizada por uma inexistente ou baixa actividade alimentar na água doce, que quando sucede é acompanhada de um ínfimo crescimento das células somáticas. O bioma onde tem lugar o crescimento e alimentação (o mar) difere do bioma reprodutivo (água doce).

(ii) Espécies catádromas, cujo crescimento e alimentação ocorrem em água doce, dando-se posteriormente a migração dos adultos para o mar, com vista à reprodução; caracterizada por inexistente ou baixa actividade alimentar no mar, ou se alguma actividade alimentar ocorre, que quando sucede é acompanhada de um baixo crescimento das células somáticas. O bioma onde tem lugar o crescimento e alimentação (água doce) difere do bioma reprodutivo (o mar).

(iii) Espécies anfídromas, cuja reprodução ocorre em água doce, dando-se posteriormente a migração de formas larvares em direcção ao mar, onde tem lugar um curto período de alimentação e crescimento, seguindo-se a migração de formas pós-larvares e juvenis em direcção a água doce, onde ocorre uma actividade alimentar prolongada e a maior parte do crescimento das células somáticas. O bioma onde tem lugar a alimentação é o mesmo do bioma reprodutivo (água doce).

Os migradores catádromos são na generalidade menos comuns do que os migradores anádromos, sendo um exemplo clássico de referência a enguia Europeia (*Anguilla anguilla*), cuja migração reprodutiva envolve distâncias de milhares de quilómetros percorridos entre os rios Europeus, onde se desenvolvem, e o Mar dos Sargaços (Noroeste do Oceano Atlântico; longitude: 40-70º Oeste, latitude: 25 -35º Norte), onde se reproduzem. Esta espécie evidencia-se pela sua ubiquidade nos rios Portugueses, nos quais a presença das seguintes espécies anádromas: truta (*Salmo trutta*), o sável (*Alosa alosa*), a savelha (*Alosa falax*) e a lampreia-marinha (*Petromyzon marinus*), é igualmente comum. Apesar da sua baixa representatividade nos nossos rios, algumas espécies anfidromas são possíveis de encontrar (eg. tainha, *Liza* sp.)

Associadas à sua capacidade de adaptação ao meio hipotónico e hipertónico, alguns migradores diádromos apresentam modificações morfológicas e fisiológicas claramente evidentes (eg. salmão; *Salmo salar*), resultantes da activação de mecanismos fisiológicos, genéticos e fisiológicos (Porcher, 1987).

Os migradores potamódromos são claramente os mais representativos nos rios Portugueses, destacando-se de entre os mesmos o barbo (*Luciobarbus* sp.), a boga (*Pseudochondrostoma* sp.) e o escalo (*Squalius* sp.).

Estimulo à migração

A migração é um fenómeno complexo, resultados da interacção entre estímulos internos e externos (Lucas e Baras, 2001). As funções fisiológicas são por conseguinte controladas pela acção de factores ambientais que originam as diferentes periodicidades de migrações e respectivos padrões. A resposta comportamental de uma espécie face ao mesmo estímulo pode então diferir de acordo com a situação (Colgan, 1993), através de uma manifestação comportamental e estrutural que varia espacialmente e temporalmente, consequência da combinação dos factores actuantes. As espécies diádromas salmonicaolas são bons exemplos desta variação comportamental, cujo ciclo migratório a respectivas características associadas a este processo, foram observados diferirem entre populações de diferentes rios (Brannon, 1984). Apesar da sua verosimilhança genética, a influência dos factores ambientais inerentes a cada local é evidente, emergindo como um dos factores condicionantes ao desenvolvimento do processo migratório. As características migratórias são por conseguinte resultado parcial da componente genética das espécies, que é fortemente influenciada pelos factores ambientais (eg. luz, temperatura, velocidade do escoamento, qualidade da água, disponibilidade de alimento) (Jonsson, 1982; Näslund, 1993). Este comportamento é também fortemente controlado pelas variações ontogenéticas das espécies, cujas alterações estruturais e motivacionais indiciam diferentes respostas aos vários estímulos existentes, resultado de processos intrínsecos (Colgan, 1993). As diferentes necessidades metabólicas dos peixes (eg. necessidade de alimentação), têm igualmente forte contribuição no desenvolvimento das deslocações dos peixes, que podem por esse propósito atingir consideráveis distâncias (Lucas e Baras, 2001).

A complexidade deste fenómeno, induziu ao desenvolvimento de vários estudo cujo objectivo prevalecia na determinação e identificação dos factores que despoletam o fenómeno da migração nos peixes (Banks, 1969; Brown e MacKay, 1995; Jonsson, 1991), dos quais emergiram diferentes teorias interpretativas, umas enaltecendo importância do caudal de escoamento dos rios (Baglinière *et al.*, 1987) enquanto outras sugeriam que a temperatura e variações associadas prevaleciam como factores determinante ao processo migratório (Clapp *et al.*, 1990; Meyers *et al.*, 1992). Ovidido *et al.* 1998, propõe uma interpretação alternativa às demais, de carisma mais generalista, na qual defende que o processo migratório é iniciado aquando da sobreposição das forças estimulantes à deslocação às forças promotoras à permanência num determinado local. A interpretação deste comportamento é por conseguinte um processo complexo, em continuo estudo e desenvolvimento.

1.2. CAPACIDADE NATATÓRIA E FACTORES ASSOCIADOS

A capacidade migratória dos peixes resulta da integração entre a capacidade locomotora e o consumo energético inerente, em combinação com a capacidade de estabilidade e orientação direccionadas para a motivação originária do movimento migratório (Lucas e Baras, 2001). As diferentes morfologias, estratégias metabólicas de consumo de energia e oxigénio das diversas espécies piscícolas, resultam em diferentes capacidades e modos de natação entre espécies (Webb, 1984).

Numa perspectiva energética, a natação pode ser considerada como um modo de transformação de energia em distância percorrida (Lucas e Baras, 2001). Durante a movimentação para jusante, os peixes assumem uma postura passiva, sendo geralmente arrastados pela currente, estando associados a este processo negligentes consumos energéticos. Em oposição, durante as suas migrações para montante, os peixes necessitam de atingir velocidades de natação muito elevadas, superiores às velocidades de corrente, com elevados gastos energéticos associados, utilizados também para atingirem o equilíbrio necessário à contínua movimentação direccionada para montante. Não obstante às diferenças referidas, as espécies migradoras apresentam também notórias variações na sua capacidade de natação, relacionadas com a sua dimensão, fase ontogenética e as condições ambientais existentes durante o período migratório (Bainbridge, 1958).

Segundo Larinier (2002a), a capacidade natatória está intrinsecamente relacionada com a ondulação do corpo e da barbatana caudal, que emergem como principais fontes de propulsão da migração, na maioria das espécies. A frequência de ondulação do peixe e da barbatana caudal é determinada pela temperatura e pelo tipo de músculo envolvido.

O tecido muscular envolvido na natação representa cerca de 50-60% da totalidade da massa muscular dos peixes (Lucas e Baras, 2001), compreendendo dois tipos de músculo, o músculo branco e músculo vermelho, cuja utilização se encontra associada a diferentes regimes de natação. O músculo vermelho, cuja coloração reflecte a alta concentração de pigmentos transportadores de oxigénio no sangue como a hemoglobina e a mioglobina, constitui uma pequena porção da totalidade da massa muscular, relativamente menor em peixes sedentários (3-5% da massa muscular) quando comparado com a respectiva representatividade nos peixes que conseguem suster uma natação rápida (15-20% da massa muscular). Este músculo está associado a uma actividade muscular aeróbia, mantida geralmente por períodos de longa duração, com velocidades reduzidas. Este regime de natação, geralmente designado por velocidade de cruzeiro " Cruising activity", pode permanecer durante horas, sem causar alterações fisiológicas, dado que o combustível requerido, a glicose, é fornecida de forma sustentada a este tipo de músculo através de inúmeros vasos sanguíneos que o irrigam (Santo, 2005). A energia requerida aquando curtos períodos de rápida natação excede a energia sustentada pelo músculo vermelho sendo necessária a activação do músculo branco. Caracterizado por uma fraca irrigação vascular, a actividade do músculo branco depende directamente da conversão anaeróbia do glicogénio em àcido lácteo. Apesar da contracção deste musculo permitir rápidas acelerações, as reduzidas reservas de glicogénio existentes no mesmo, incutem ao rápido esgotamento desta substância, e, paralelamente, à acumulação do acido láctico que por sua vez inibe a contracção do músculo, tornando este regime natatório apenas possível durante curtos períodos de duração, na ordem dos segundos (Beamish, 1978; Wardle, 1975). Este tipo de actividade assume a designação de velocidade de explosão "Burst speed" (Blaxter, 1969; Bell, 1986 e Webb, 1975). A actividade natatória pode ainda resultar da acção simultânea de processos anaeróbios e aeróbios, que pode ser mantida durante alguns minutos causando porém cansaço no peixe, prevalecendo o aumento da componente anaeróbica com o aumento do esforço. Este tipo de actividade assume a designação de velocidade sustentada "Sustained activity".

A utilização dos diferentes tipos de natação, surge como resposta motivacional, pelo que Bell (1986) sugere que, geralmente, os peixes utilizam a velocidade de cruzeiro para se movimentarem (mesmo durante a migração), a velocidade sustentada para a passagem por condições de fluxo de maiores velocidades e a velocidade de explosão para propósitos de alimentação e fuga. A cada uma das velocidades características de nado está associado um nível de exigência energético muscular diferente, no qual se assume a existência de uma perda de 15% de energia na transformação da energia muscular em propulsão (Bell, 1986).

A velocidade de natação é determinada pelo comprimento do peixe e a frequência de oscilação do mesmo, enquanto que a distância percorrida depende do comprimento do movimento do peixes e da frequência dos batimentos da barbatana caudal.

A distância (*Dist*) que pode ser percorrida por um peixe contra a corrente, pode ser avaliada a partir da seguinte equação apresentada por Larinier (2002b):

$$Dist = (Vpeixe\text{-}\ V)\cdot t \qquad (1.1)$$

onde, *Vpeixe* a velocidade de nado do peixe, *V* a velocidade do escoamento e *t* o tempo de resistência do peixe ao escoamento.

Durante a movimentação para montante, os peixes são sujeitos a forças actuantes sobre os mesmos, que podem ser definidas através de:

$$F_D = \frac{1}{2}.\rho.U^2.A.C_D \qquad (1.21)$$

onde, F_D representa a componente da força na direcção do escoamento, que é denominada por arrasto, ρ a massa específica da água, U a velocidade resultante sobre o peixe (velocidade de nado – velocidade do escoamento), *A* a área da secção transversal do corpo do peixe, que pode ser simplificada para a área de uma elipse, e C_D o coeficiente de arrasto. A definição deste coeficiente deve ser obtido experimentalmente, sendo utilizado para o cálculo do trabalho (W) realizado pelos peixe ao percorrer uma determinada trajectória de comprimento (D), de acordo com o proposto por Bell (1986):

$$W = F_D.D = F_D.V.t \qquad (1.3)$$

onde, F_D é o coeficiente de arrasto, C a distância percorrida, V a velocidade de deslocamento (Velocidade de nado – Velocidade do escoamento) e t o tempo utilizado na actividade.

A amplitude do movimento do peixe, é característica para cada espécie, dependendo da proporção dos músculos natatórios, bem como da forma, comprimento da barbatana caudal estrutura das barbatanas e amplitude dos movimentos laterais do peixe. Nesta perspectiva vários estudos têm sido desenvolvidos, visando correlacionar as velocidades de natação com as características físicas dos indivíduos. No entanto a informação disponível é escassa e bastante limitada, já que, geralmente, restringe-se a determinadas espécies.

Segundo Wardle (1975) , a distância percorrida pelo peixe a cada ondulação do corpo está entre 0,6 e 0,8 o comprimento do corpo. Assim, tem-se que a velocidade de natação (V) pode ser expressa por:

$$V = Dist\cdot f \ \text{ ou } V = 0.7\cdot l\,/\,2.t_{min} \qquad (1.4)$$

onde, *Dist* é a distância percorrida pelo peixe, *f* a frequência de ondulação do corpo e da barbatana caudal, *l* o comprimento do peixe e t_{min} o tempo mínimo entre duas contracções dos músculos que garantem a propulsão do peixe. Segundo o mesmo autor (Wardle, 1975), o tempo entre duas contracções musculares consecutivas é menor em peixes menores. O autor verificou também que além do comprimento do peixe, a temperatura é igualmente uma variável que fortemente influencia o comportamento natatório das espécies, sugerindo deste modo que as velocidades máximas dependem especialmente do comprimento do peixe e da temperatura da água.

Outro factor importante considerado por Beach (1984) é o tempo que o peixe resiste a velocidade máxima. Esse tempo depende do comprimento do mesmo, da temperatura da água e da quantidade de glicogénio armazenado nas células dos músculos brancos. Deste modo, para um determinado comprimento, o aumento na temperatura resulta na diminuição da resistência, uma vez que maiores temperaturas relacionam-se com maiores velocidades máximas, e consequentemente com uma taxa de depleção maior das reservas de glicogénio nos músculos.

Baseado nos resultados experimentais (obtidos para peixes com comprimentos inferiores a 55 cm), Viedeler (1993) relaciona a velocidade máxima de natação, $V_{max\ nat}$ (m.s^{-1}) e o comprimento do peixe, l (m) através da equação:

$$V_{maxnat} = 0.4 + 7.4 \cdot l \qquad (1.5)$$

Bell (1986) aponta para alguns migradores anádromos adultos, velocidades máximas possíveis em condições óptimas de temperatura de aproximadamente 6 a 8 m.s^{-1} para o salmão, 3 a 4 m.s^{-1} para a truta e 4 a 5m.s^{-1} para o sável, sendo que este último apenas consegue manter estas mesmas velocidades durante curtos períodos de tempo.

Porcher (2002) por sua vez indica velocidades de natação máximas para indivíduos juvenis de enguia (espécie catádroma), com dimensões compreendidas entre 10 a 40 cm, de 0.6 a 0.9 m.s^{-1}, evidenciando a reduzida capacidade natatória dos mesmos.

Relativamente à velocidade de cruzeiro, definida como a velocidade máxima a que o peixe consegue nadas sem exibir sinais de fadiga, o mesmo autor propõe duas relações entre a velocidade de cruzeiro, V_{cr} (m.s^{-1}) e o comprimento do peixe l, (m); igualmente obtidas em experiencias conduzidas com peixes de dimensões inferiores a 55cm.

$$V_{cr} = 0.15 + 2.4 \cdot l \qquad (1.6)$$

$$V_{cr} = 2.3 \cdot l^{\wedge 0.8} \qquad (1.7)$$

Em ambas as relações é evidente a importância do comprimento do peixe na sua capacidade natatória.

Videler (1993), aponta para alguns migradores anádromos de dimensões inferiores a 55 cm, velocidades de cruzeiro de aproximadamente 1.7 a 2.5 $m.s^{-1}$ para o salmão e 0.6 a 1.3 $m.s^{-1}$ para a truta.

Influência da turbulência do escoamento na capacidade natatória e comportamento dos peixes

A capacidade natatória dos peixes é também fortemente dependente das características físicas dos próprios rios, como a turbulência do escoamento (Hawkins., 1993). Esta variável hidráulica, pode despoletar ou mesmo prevenir o comportamento migratório dos peixes, de acordo com a sua forma e grandeza de actuação no corpo do mesmo (Lupandin, 2005; Odeh *et al*, 2002). A turbulência, é uma variável hidráulica indicadora da movimentação irregular de partículas no escoamento (escoamento turbulento) e das respectivas flutuações de velocidades inerentes. A consideração do tamanho destas flutuações (escala de turbulência), emerge como factor fundamental ao entendimento dos impactos desta variável nos peixes. Pequenas escalas de turbulência, geralmente associadas à passagem dos peixes nas turbinas, provoca compressão e distorção dos peixes, enquanto que escalas maiores estão relacionadas principalmente com a desorientação da movimentação dos peixes (Odeh *et al.*, 2002). No entanto a turbulência, surge também com factor favorável à movimentação dos peixes, como indicado por Coutant e Whitney (2000), que sugerem que a turbulência é utilizada pelas espécies migradoras anádromas durante a migração para jusante.

O entendimento sobre como os peixes sentem, reagem e usam este fenómeno hidráulico e respectivas componetes (ex. energia cinética da turbulência, tensões de Reynolds e intensidade de turbulência) na sua movimentação, tem-se relevado extremamente importante, suscitando o desenvolvimento de vários.

O desenvolvimento de projectos que visem a diminuição dos impactos da turbulência nos peixes aquando da sua passagem pelas turbinas, surge como um dos principais interesses de investigação. Cada *et al.* (1997) , tentou avaliar as tensões a que os indivíduos estão sendo submetidos e os respectivos efeitos de pressão e tensão resultantes.

Odeh *et al.* (2002) estudou o efeito das tensões de Reynolds nos peixes, sugerindo q estas tensões podem representar de maneira adequada o efeito da turbulência sobre o corpo dos mesmos. Os efeitos de tensões podem então ser descritos como forças actuantes paralelamente ao corpo, cujos valores elevados, geralmente associam-se a danos na mucosa dos peixes.

Turnpenny *et al.* (1992) submeteu diferentes espécies de peixes a tensões entre os 206 e 3410 N.m^{-2}, e avaliou os danos resultantes. Os salmonídeos; salmão do atlântico (*Salmo salar),* truta arco-íris (*Onchorhynchus mykiss*) e *truta marisca (Salmo trutta trutta*) testados com os menores valores de tensões apresentaram pouca ou nenhuma perda de camada da mucosa e nenhum outro dano aparente, e não ocorreu mortalidade após sete dias a exposição única. O aumento das velocidades e das tensões aumentou os danos e diminuiu o tempo de sobrevivência. Para o máximo valor testado (3410 N.m^{-2}), observou-se uma perda da camada da mucosa e danos nos olhos, com sobrevivência após 7 dias de 90% dos indivíduos. Já os clupeídeos (peixes da família Clupeidae), mostraram-se bem mais sensíveis aos ensaios realizados e, mesmo para as tensões menores, morreram dentro de uma hora, sofrendo danos ou perda dos olhos, perda da mucosa, entre outros. Este estudo evidencia que o impacto da turbulência diverge entre espécies.

Odeh *et al.* (2002) procurou verificar o efeito da turbulência no comportamento de peixes migratórios, através do estudo de três condições de turbulência a jusante de uma comporta. Esses pesquisadores avaliaram três espécies de peixes: truta arco-íris (*Onchorhynchus mykiss*)*,* robalo híbrido (*Morone saxatilis* x *Morone chrysops*), e salmão do atlântico (*Salmo salar*). Odeh *et al.* (2002) verificaram que a exposição a tensões de Reynolds médias superiores a 50 N.m^{-2}, por um período de 10 minutos, pode causar algum dano as espécies, mas não causa mortalidade significante após 48 horas da exposição. Para valores superiores a 30 N.m^{-2}, Odeh *et al.* verificaram que não há alteração da resposta da truta arco-iris *contrariamente* ao observado nos exemplares juvenis de salmão do atlântico e do robalo híbrido (*Morone saxatilis* x *Morone chrysops*), cujo comportamento é fortemente influenciados mesmo por essas tensões, deixando-os deste modo mais susceptíveis aos predadores ou outros riscos. Os autores ainda verificaram que os peixes estavam recuperados dos efeitos da turbulência 24 horas depois dos ensaios. Lupandin (2005) avaliou o efeito da turbulência do escoamento na velocidade de natação da espécie *Perca fluviatilis*, em indivíduos de diferentes tamanhos. Nesse estudo, verificou-se que a partir de um determinado valor de intensidade da turbulência (razão entre o desvio padrão da série temporal e a velocidade média) os peixes diminuem a velocidade de nado. Lupandin (2005) relata que a diminuição na capacidade natatória inicia quando a escada de turbulência, que descreve o tamanho do vórtice, excede 2/3 do comprimento do peixe.

Observa-se, a partir de estudos onde se verifica a influência da turbulência do escoamento na capacidade natatória que, fluxos excessivamente turbulentos prejudicam o desempenho dos movimentos dos peixes. No entanto, Liao *et al.* (2003), verificou que os peixes podem utilizar-se dos vórtices formados no escoamento para reduzir os "custos de locomoção". Esses autores comentam que a compreensão da interacção entre a actividade muscular dos peixes e a passagem através dos vórtices promete auxiliar nos projectos de escadas de peixe.

1.3. A MIGRAÇÃO NOS CIPRINÍDEOS

Considerações gerais

Os ciprinídeos são o principal grupo de espécies piscícolas de água doce, compreendendo cerca de 1700 espécies (Lucas e Baras, 2001). Fortemente representados nos rios Europeus, abrangendo aproximadamente 42% da totalidade das espécies dos sistemas fluviais (Lelek, 1987), ocupam uma variedade de habitats desde lóticos a lênticos, sendo os últimos os mais associados à sua existência. Apesar da escassa informação sobre a capacidade migratória dos ciprinideos (Mills, 1991; Smith, 1991), um grande numero de ciprinideos exibem migrações para reprodução, pelo que estudos têm vindo a ser recentemente desenvolvidos, principalmente na Europa e América do Norte, focados na identificação dos padrões migratórios destas espécies.

As deslocações das espécies ciprinicolas ocorrem essencialmente durante a primavera, e com propósitos de reprodução. Tendo como finalidade alcançar habitats propícios à desova, os diferentes espécimes podem então efectuar deslocações que oscilam entre curtas e longas distancias, dependendo da espécie. Na generalidade os peixes adultos permanecem nesse habitat durante o Verão, para se alimentarem. Durante o Inverno, as poucas deslocações observadas incidem fundamentalmente em deslocações para locais mais profundos, ou para locais com menores velocidades (Lucas e Baras, 2001).

O início do ciclo reprodutivo dos ciprinídeos, está associado a alterações fotoperiodicas (Mills, 1991; Northcote, 1998) e ao aumento da temperatura (Rodríguez-Ruiz e Granado-Lorencio, 1992; Santos *et al.*, 2002). Para evitar o risco de predação na generalidade os espécimes efectuam as migrações ao fim do dia perante médias a baixas intensidades de luminosidade (Cerri, 1983), pelo que este último factor emerge igualmente como importante condicionante ao processo migratório (Lucas e Baras, 2001). A influencia deste factores neste fenómeno, varia sazonalmente e com as condições climatéricas. Deste modo, se as temperaturas óptimas à migração, ocorrerem durante o dia a deslocações são efectuadas durante esse período, mesmo com o inerente factor de risco associado (predação) (Baras, 1995). Não obstante, perante o mesmo estímulo ambiental as espécies apresentam respostas comportamentais distintas entre estas, pelo que a esses estímulos (ex. temperatura e intensidade luminosa) se sobrepõem as especificidades de cada espécie. Caracterizados por uma fraca capacidade de natação e de salto, durante as suas migrações para montante, as espécies ciprinicolas enfrentam comummente dificuldade inerente à transposição de barreiras naturais e artificiais, que obstruem a sua contínua deslocação. Atendendo a estas limitações físicas, consideráveis esforços têm sido feitos para facilitar a passagem para montante desta e de outras espécies com semelhantes limitações. Jungwirth (1996) e Schmutz *et al* (1995), verificaram que a introdução de um canal naturalizado adjacente ao leito do rio principal resultou num considerável sucesso de passagem para montante destas espécies.

O barbo Ibérico (*Luciobarbus bocagei*, Steindachner 1865)

O barbo Ibérico (*Luciobarbus bocagei* Steindachner, 1865), ciprinídeo endémico da Península Ibérica, existe na maioria das bacias hidrográficas do norte e centro de Portugal. Esta espécie é dos ciprinídeos mais comuns e amplamente distribuídos, existente numa vasta gama de habitats lóticos e lênticos (Magalhães, 1992). Com consequente elevado interesse ecológico encontra-se nas espécies consideradas não ameaçadas na Península (Doadrio, 2001;). Caracterizado por habitar áreas com baixo ou moderado de corrente da água, apresenta uma forte sazonalidade migratória que se inicia em Abril, cujo pico ocorre em Maio. Este potamódromo efectua migrações para montante, para desovar em zonas arenosas e de correntes rápidas (Rodríguez-Ruiz e Granado-Lorencio,1992). Os espécimes de ambos os sexos iniciam as suas deslocações com fins reprodutivos (Lucas e Batley, 1996; Lucas e Frear, 1997), mas provavelmente devido à sua maior dimensão ou preferência por locais com características mais lênticas fora da época reprodutiva, as fêmeas podem percorrer distancias superiores (Baras, 1992). Durante o período migratório esta espécie é fortemente atraída pelo forte fluxo de corrente (Baras e Cherry, 1990; Baras *et al.*, 1994), evidenciado a sua natureza reostáctica.

1. 4. IMPACTES DAS OBRAS HIDRÁULICAS NAS COMUNIDADES PISCÍCOLAS

A utilização da água pelo Homem, remonta de à vários milhares de anos. A disponibilidade deste recurso essencial á vida, é então responsável pelas deslocações dos povos nómadas, os quais mais tarde se estabilizaram em zonas de fácil acesso a este precioso recurso, dsenvolvendo as primeiras grandes sociedades humanas. A construção de infra-estruturas hidráulicas para retenção de água para consumo e rega de campos nessas mesmas sociedades, emerge então como principal factor do seu desenvolvimento. Deste modo a construção de obras hidráulicas constitui certamente uma das mais antigas e difundidas obras de engenharia (Baxter, 1977).

Actualmente, a construção de infra-estruturas hidráulicas originadas por diferentes motivod é procedimento comum, pelo que a maior parte dos rios se encontram regularizados (Ward e Stanford, 1979; Petts, 1984), estimando-se que aproximadamente metade da água doce disponível no planeta esteja retida em mais de 800.000 albufeiras (Rosenberg *et al.*, 2000). Associadas a esta exacerbada construção surgem alterações dramáticas na estrutura, composição e diversidade das comunidades piscícolas, devido a alterações humanas ao nível do seu habitat (Copp, 1990; Gehrke *et al.*, 1995; Peňáz *et al*,. 1999; Ward e Stanford, 1979).

Segundo Chiu *et al.* (2002) as principais causas da diminuição da população de peixes devem-se a três factores: pesca excessiva, poluição e bloqueio dos rios, sendo que a fragmentação dos rios representa a causa mais insidiosa. Os dois primeiros problemas são de reconhecimento geral pela maior parte da população e da comunidade científica. Por outro lado, a fragmentação dos rios, pelo bloqueio imposto pela construção obras hidráulicas passa muitas vezes despercebido pela sociedade, pelas facilidades advindas da construção das mesmas, como abastecimento de água, geração de energia, recreação, entre outros. Outro factor relevante é que a poluição e a pesca predatória afectam indivíduos isolados dentro da comunidade aquática, enquanto que o bloqueio dos rios interfere no habitat dos peixes, principalmente nos migratórios, podendo levar à extinção de espécies piscícolas dulçaquícolas.

A regularização dos rios é, com efeito, o factor antropogénico com impactes mais significativos ao nível da alteração do habitat para as espécies dulçaquícolas, estimando-se que aproximadamente 77% dos caudais totais dos 139 maiores rios da América do Norte e Europa, se encontrem alterados (Cowx e Welcomme, 1998). A Península Ibérica não é alheia a esta situação mundialmente generalizada. Com efeito, a irregularidade climática e consequentemente, dos caudais dos rios Ibéricos, incentivaram uma intensa regularização, que se traduziu na construção de mais de 1000 grandes barragens durante os últimos 100 anos (MMA 1998). Em Portugal, todos os grandes rios e a maior parte dos rios de média dimensão encontram-se regularizados por mais de 150 barragens e aproximadamente 100 pequenos aproveitamentos hidroeléctricos (PAH).

A construção de obras hidráulicas como açudes e barragens, produz, um impacte significativo nas populações piscícolas, principalmente nível dos movimentos migratórias que são impedidos ou sofrem atrasos consideráveis, bem como na afectação da disponibilidade e acessibilidade dos habitat, que desempenham uma importante função na sustentabilidade das populações, podendo assim comprometer irremediavelmente a sobrevivência das espécies (Lenne, 1990).

Não obstante dos efeitos de obstrução física associados à implantação de obras hidráulicas nos cursos de água, muitos outros surgem com igual impacto nas comunidades piscícolas. Destacam-se entre eles as alterações: do escoamento (ex. regime de caudais), da granulometria e dos locais de deposição de sedimentos e da qualidade da água (ex. diminuição do teor de oxigénio). Salienta-se ainda, o aumento do risco de predação a montante e a jusante, pela concentração junto ao obstáculo de um grande número de indivíduos, que são impedidos ou atrasados na sua deslocação, constituindo um alvo fácil para determinados predadores e para a pesca.

Os diferentes impactos inerentes à construção de barragens e açudes são sistematizados e classificada de acordo com a sua ordem de grandeza por Petts em 1988. O autor divide os diferentes impactos em três ordens, sendo que os de primeira ordem conduzem aos de segunda que por sua vez dão origem aos de terceira ordem. Nos de primeira ordem foram considerados: o efeito de barreira à livre circulação das espécies; a alteração do regime natural de caudais; a alteração de granulometria e de locais de disposição de sedimentos, bem como a sua quantidade; alterações na qualidade da água a jusante, especialmente se as descarga forem no hipolimnio e, alterações quantitativas e qualitativas no plâncton. Estes condicionam os impactes de segunda ordem que incluem: alterações frequentes na forma do canal fluvial e na distribuição de habitats e; alterações na distribuição, no tipo e quantidade de plantas. Estes influem nos impactes considerados de terceira ordem que incluem alterações na comunidade de macroinvertebrados e de peixes (composição e biomassa).

1.5. RESTAURAÇÃO DA CONECTIVIDADE LONGITUDINAL: PASSAGENS PARA PEIXE

A conectividade longitudinal de um rio, é em termos ecológicos, factor essencial para satisfazer as diversas necessidades das diferentes espécies aquáticas, devendo por isso ser conservada e restaurada. A introduçã de passagens para peixes, permite restabelecer a conectividade dos rios, interrompida pela implantação de infra-estruturas hidráulicas nos rios.

Um dispositivo de passagens para peixes, é em termos gerais, um caminho alternativo ao curso de água, no qual foi instalado um obstáculo intransponível ou dificilmente transponível (Bochechas, 1995). O principio geral de funcionamento de uma passagem para peixes, consiste em atrair os mesmos a um determinado ponto a jusante de um obstáculo, induzindo-os ou fazendo-os passar para montante através de um caminho com água (passagem para peixes em sentido estrito) ou capturando-os num tanque ou estrutura similar, sendo posteriormente transferidos para montante (ascensores e sistemas de captura e transporte) (Larinier 2002a). Uma passagem para peixes é então considerada eficiente se os peixes encontrarem facilmente a sua e a transponham sem dificuldades significativas, sem atrasos excessivos ou stress que possam prejudicar a sua migração.

Por conseguinte, o dimensionamento de uma passagem para peixes deve ter em conta determinados aspectos do comportamento das espécies migradoras, nomeadamente a capacidade natatória das mesmas. A eficácia deste tipo de dispositivos hidráulicos, depende da capacidade de integração, aquando da sua concepção, de conhecimentos de índole biológica (fisiologia, biomecânica ecologia das espécies) com conhecimentos na área da hidráulica e hidrodinâmica (velocidade da água e regime de escoamento) (Larinier, 2002a; Pavlov, 1989). As velocidades da água na passagem para peixes devem ser compatíveis com as capacidades natatórias das espécies consideradas. Algumas espécies são muito sensíveis a determinados regimes de escoamento ou condições: quedas entre bacias demasiado elevadas, turbulência excessiva, existência de remoinhos ou velocidades da água demasiado baixas, podem actuar como barreiras à migração. Por outro lado, além dos referidos parâmetros hidráulicos, existem ainda outro tipo de factores, como sejam o teor de oxigénio dissolvido, temperatura da água, ruído, luz, odor, que podem condicionar a passagem de cada espécie, nomeadamente se a qualidade da água que alimenta a passagem para peixes, for diferente daquela proveniente da obra hidráulica (Larinier, 2002e).

1.6. EVOLUÇÃO HISTÓRICA DAS PASSAGENS PARA PEIXES

No Mundo

Por razões várias, a utilização e manipulação dos sistemas aquáticos fluviais, remonta de à vários séculos atrás. Já povos indígenas da Costa do Pacifico e das regiões interiores da América do Norte construíam açudes e outros artifícios, para facilitar a captura de espécies que utilizavam na sua dieta, entre as quais se destaca o salmão e a truta (Northcote, 1998). Mais recentemente, com propósitos, de índole não tão primária; têm a vindo a ser desenvolvidas obras hidráulicas nos cursos de água, principalmente destinadas à produção eléctrica e à reserva de água. Não obstante à ruptura do continuo lótico resultante da presença destas obras nos sistemas fluviais, estas emergem ainda como principais responsáveis à obstrução das rotas migratórias e da consequente diminuição das comunidades piscícolas, que no limiar pode resultar na extinção das espécies (Lucas e Baras, 2001). Na tentativa de minimizar os impactos causado sobre a fauna piscícola, resultantes da implantação dessas obras transversais fluviais, foram desenvolvidos dispositivos hidráulicos, denominados por passagens para peixes, que visavam possibilitar a transponibilidade desses obstáculos. Estas são por conseguinte de grande importância à restauração das deslocações contínua ao longo dos rios, efectuadas pelas espécies migradoras (Clay, 1995). A implantação da primeira passagem para peixes; com uma altura pouco superior a 2 m; remonta ao século. XVII (1640), na cidade de Berna (Suíça), especificamente no rio Aar. A partir desse período observou-se que o uso de escadas para peixes foi sendo difundido para outras partes do mundo, que perceberam a necessidade da preocupação com a questão da transposição de peixes. Segundo Kamula (2001), a necessidade de dispositivos para a transposição dos peixes aumentou por volta de 1850, coincidindo com a produção de turbinas hidráulicas e a implantação de aproveitamentos hidroenergéticos em maior escala.

È então 1852 em Sligo, Irlanda, que é construída a primeira grande passagem para peixes com sucesso: a passagem para peixes de Balliisodare (McGrath, 1956). Com o avanço industrial (Revolução Industrial; finais de séc. XVIII - inicio de séc. XIX), o desenvolvimento e implantação de estruturas hidráulicas (ex. barragens) aumenta, suscitando uma maior necessidade de construir passagens para peixes mais eficientes. Segundo Balaque da Silva (Silva, 1896) em 1896, existem já diversos tipos de passagens para peixes, sendo o sistema mais adoptado o de escadas para peixes, ainda porém que bastante arcaico. O mesmo, consistia num conjunto de reservatórios quadrados dispostos uns por cima dos outros, formando uma série de cascatas que os peixes teriam que transpor saltando. Paralelamente em Inglaterra e na América, eram mais utilizados os dispositivos de plano inclinado, com compartimentos rectangulares (Silva, 1896). Em 1909, é feita uma publicação porum cientista Belga (G.Denil), ondeé exposto um novo modelo de passagens para peixes: passagens para peixes do tipo Denil, extremamente avançado, que permitia uma excelente dissipação de energia, tendo sido implantado para funcionamento na Bélgica por volta de1920 (Clay, 1995). A implantação e dispositivos para passagem de peixes, é desde então processo corrente aquando da construção de obras hidráulicas em todo o Mundo. Em 1985, é apresentado por Godoy um trabalho de índole histórica, sobre a evolução mundial das passagens para peixes.

Em Portugal

Em Portugal a construção de passagens para peixes é um fenómeno relativamente recente, sendo a referência mais antiga conhecida, a passagem de deflectores instalada na barragem de Belver em 1951 (Silva, 1991). Este dispositivo do tipo escada para peixes, revelou-se ineficaz, tendo sido posteriormente substituído por uma eclusa em 1983, que entrou em funcionamento apenas três anos mais tarde 1986 (Silva, 1991). No entanto, referências anteriores a esta estrutura, indicam a possível existência de dispositivos de passagem para peixes. De facto, a passível existência destas estruturas é concordante com o estabelecido nos artigos 165-166 do Regulamento dos Serviços Hidráulicos de 19 de Dezembro de 1892e no nº 3ºdo Regulamento Geral dos Serviços Aquícolas de 20 de Abril de 1893, nos quais se determina que "nos açudes e represas estabelecidos nos leitos de corrente d'águas interiores se estabeleçam escadas para a subida dos peixes".

A partir da segunda metade do século passado, verifica-se um forte incremento na construção de passagens para peixes, resultado de uma acentuada regressão de algumas espécies piscícolas, em particular das diádromas. Este fenómeno surge como resultado da intensa construção de barragens, e aproveitamentos hidroeléctricos de pequena escala (PAH) e outro tipo de açudes, que altera escoamento natural dos cursos de água e, consequentemente, o funcionamento ecológico dos mesmos, como a livre circulação das espécies piscícolas, fundamental para a realização das diferentes fases dos seus ciclos biológicos.

O desenvolvimento exacerbado de obras hidráulicas observado em Portugal nessa época , emerge como resposta à existente limitação dos recursos hídricos. Aqui, onde a orografia, a precipitação e as influências atlânticas e mediterrâneas determinaram uma distribuição irregular das disponibilidades hídricas no espaço e no tempo (Santos, 2004), a necessidade de construir barragens e açudes com propósito primordial de armazenar água capaz de garantir o fornecimento de água para rega, bem como para abastecimento público, sobretudo nas regiões de maior irregularidade hídrica, particularmente no Sul; surge como factor fundamental. Por motivos outros, Por outro lado, no Norte do país, onde os recursos são mais abundantes e regulares, foram construídos aproveitamentos (cerca de 40), maioritariamente dirigidos para a produção de energia. Em Portugal, tal como em muitos outros países, mais de metade das cerca de 150 barragens (estruturas com mais de 15 m de altura) e mais de 3000 pequenos açudes hoje inventariados, foram construídos nos últimos 35 anos, por via do forte crescimento da procura de água (Afonso, 2001). Para além dos demais, existem ainda muitos outros pequenos açudes, em particular a norte do rio Tejo (Santo, 2005), que apesar de abandonados e/ou em lastimável estado degradação, constituem ainda obstáculo à livre circulação dos peixes.

Apesar do elevado número de barragens e açudes, em Portugal, existem apenas cerca de 39 dispositivos de passagem para peixes conhecidos: 31 passagens para peixes de bacias sucessivas, sendo que a grande maioria se encontra instalada em PAH; 6 eclusas Borland, das quais 5 se encontram instaladas no rio Douro e uma no Tejo; 1 ascensor, instalado na barragem do Touvedo, rio Lima; e uma passagem naturalizada (canal naturalizado), igualmente no rio Lima. A maioria dos mesmos ou não se encontra em funcionamento ou demonstram ser ineficientes à passagem dos peixes (Santo, 2005). Um dos principais motivos da ineficácia destes dispositivos hidráulicos, resulta do inadequado dimensionamento dos mesmos, para a passagem das espécies piscícolas migradoras existentes em Portugal.

O início da elevada construção de obras hidráulicas durante a última década, suscitou a obrigatoriedade de implantação de passagens para peixes aquando da construção das mesmas. A implantação de diapositivos de passagens para peixes é então realizada, mediante a concepção importada de projectos elaborados em outros peixes, e cujos critérios de dimensionamento tinham sido estudados considerando espécies, outras que não existentes/comuns nos rios Portugueses. O dimensionamento destes dispositivos, que se demonstrara eficiente nos outros países, evidencia então grande limitação à passagem das espécies migradoras comuns dos nossos rios, cujas características biomecânicas diferem grandemente das espécies para as quais os dispositivos tinham sido projectados.

Além da ausência de estudos publicados sobre passagens para peixes, particularmente das por bacias sucessivas (tipo de passagem mais comum em Portugal), as espécies que se predispõem a utilizar este tipo de dispositivos são essencialmente espécies potamódromas, nomeadamente barbos, bogas e escalos, para as quais o conhecimento acerca da sua ecologia e modo de utilização deste tipo de dispositivos hidráulicos, é altamente escasso (Santos, 2004). O desenvolvimento de estudos focados no funcionamento deste tipo de dispositivos hidráulicos para estas espécies, é por conseguinte extremamente importante, permitindo a futura evolução das passagens para peixes em Portugal, promovendo a qualidade e a continuidade dos cursos de água portugueses.

1.7. Tipos de Dispositivos de Passagens para Peixes

A multiplicidade de factores (biológicos, hidrológicos, hidráulicos, topográficos, etc.) característicos de determinado local, assim como a complexa interacção entre os mesmos, conduza uma dificuldade acrescida aquando da selecção do tipo de dispositivos de passagens para peixes a implantar. Cada situação é então um caso específico (Larinier, 2002a), devendo ser considerados os seguintes aspectos durante esse processo: as espécies piscícolas presentes no local, as características hidrológicas do curso de água, as características do obstáculo (infra-estrutura hidráulica), o caudal a transitar no interior da passagem, as variações de nível a montante e a jusante, a topografia, o desnível a vencer e o custo de funcionamento (Porcher e Larinier, 2002).

As características biomecânicas das espécies existentes no curso de água, são factor determinante à selecção o tipo de dispositivo a utilizar. Este processo deve então incidir primordialmente na espécie que apresenta características mais restritivas, procurando assegurar deste modo um adequado funcionamento para o maior número de espécies piscícolas existentes. Relativamente às características da infra-estrutura –hidráulica, a altura e o respectivo desnível a vencer, apresentam-se como as mais limitativas à selecção do tipo de passagem a utilizar. Para grandes alturas e desníveis a melhor solução será então a utilização dos designados ascensores.

De acordo com a classificação apresentada pela FAO, (FAO/DVWK 2002), as passagens para peixes podem ser de três tipos:

i) Passagens tradicionais "*Technical structures*" :
  - passagens por bacias sucessivas (*Pool passes or Fish ladders*);
  - deflectores ou tipo Denil (*Denil passes*);

ii) Passagens naturalizadas *"Close-to-nature types of structures":*
  - Rampas e declives escavados (*Bottom ramps and slopes*);
  - Canais naturalizados (*Bypass channels*);
  - Rampas para peixes (*Fish ramps*).

iii) Passagens especiais *"Special constructions":*
  - Passagens para enguias *(Eel ladders)*
  - Eclusas *(Fish locks)*
  - Ascensores *(Fish lifts)*

A escolha do tipo de dispositivo a utilizar, prende-se essencialmente com o desnível a vencer e no caso das passagens naturalizadas, com as características do local. (Santo, 2005). Seguidamente são apresentados e brevemente caracterizadas as características principais de funcionamento dos diferentes tipos de passagens para peixes.

Passagens tradicionais “*Technical structures*”

Escadas para Peixes ou Passagens para Peixes por Bacias Sucessivas *(Pool passes or Fish ladders)*

As passagens para peixes por bacias sucessivas são o tipo de dispositivo comummente utilizados para a transposição de obstáculos naturais e artificiais de pequena e média dimensão (ex. aproveitamentos hidroeléctricos e pequenos açudes) (Borghetti *et al.* 1994; Guiny *et al.* 2003; Jensen e Aass 1995; Linlokken 1993; Santo, 2005), são adequadas para situações em que existem frequentes variações do nível de água a montante (Schwalme *et al.* 1985; Laine *et al.* 1998; 2002; Stuart e Berghuis 2002). Dada à elevada variabilidade hidrológica dos rios Portugueses, e pela sua adequação a várias espécies (Larinier, 2002c), este tipo de passagens é o mais comum em Portugal, sendo considerado como o mais adequado à passagem de espécies potamódromas de grande representatividade na maioria dos rios Portugueses. Até à data foram contabilizados 32 dispositivos de passagem para peixes deste tipo), O principio de funcionamento deste tipo de dispositivos consiste na divisão do desnível entre os planos de montante de jusante em pequenas quedas transponíveis pelos peixes, formando uma série de bacias que se dispõem sucessivamente a diferentes níveis, formando um canal pelo qual os peixes se podem deslocar. As bacias têm duplo objectivo: proporcionar a dissipação da energia do escoamento e providenciar zonas de descanso (Larinier, 2002c). Existe uma grande diversidade deste tipo de passagens, baseado nas inúmeras combinações possíveis das dimensões das bacias, tipos de interligação e desnível entre estas.

Os peixes passam de uma bacia para a seguinte saltando ou nadando através da lâmina de água, consoante o tipo de descarregador adoptado. Os tipos de passagens de bacias sucessivas mais comuns, e que têm sido objecto de diversos estudos (Borghetti *et al.*, 1994; Jensen e Aass, 1995; Laine *et al.*, 1998,2002; Stuart e Berghuis, 2002), são aquelas em que a passagem da água entre bacias é feita ou i) por descarregadores de superfície e/ou através de orifícios submersos situados nas paredes de separação entre bacias (*pool passes*), ou ii) por fendas verticais (*vertical-slot passes*).

Uma passagem de bacias sucessivas com descarregadores de superfície e orifícios submersos consiste num canal em betão, ao longo do qual são dispostas paredes de separação em betão ou madeira (septos), com aberturas, no topo (descarregadores) e no fundo (orifícios submersos). Inerentes à utilização deste tipo de passagem estão associadas algumas desvantagens direccionadas principalmente para o risco considerável de obstrução, nomeadamente nos orifícios, por folhas, ramos e outros materiais de pequena dimensão. No entanto, as mesmas demonstram ser adequadas para todas as espécies piscícolas, desde que as respectivas bacias e orifícios sejam dimensionados de acordo com as espécies que ocorrem naturalmente no local. Relativamente às passagens por fendas verticais, estas suportam escoamentos relativamente elevados, formando deste modo, boas correntes de atracção para os peixes. Comparativamente às passagens com orifícios submersos e descarregadores de superfície, sob o ponto de vista de manutenção, apresentam um baixo risco de obstrução das fendas verticais. Actualmente constituem o melhor tipo tradicional de passagem para peixes, sendo adequada para todas as espécies piscícolas, bem como para macroinvertebrados, particularmente se o fundo for revestido por uma camada de substrato grosseiro.

Os principais parâmetros de uma passagem de bacias sucessivas são as dimensões das bacias e as características geométricas das paredes de separação entre estas (dimensão dos descarregadores, fendas e orifícios). Estas características geométricas, em função dos níveis de água a montante e jusante do referido dispositivo, determinam o comportamento hidráulico da passagem, ou seja, o respectivo caudal, a diferença de nível da água entre duas bacias consecutivas e o padrão de escoamento entre bacias (Larinier, 2002c).

De uma forma geral, a concepção e construção deste tipo de dispositivo é relativamente simples, não exigindo caudais muito elevados para o seu funcionamento, podendo comportar uma vasta gama de caudais e alguma flutuação nos níveis de água a montante e jusante. O seu funcionamento é permanente, salvo quando determinados condicionalismos específicos, e de fácil verificação.

Deflectores ou tipo Denil (Denil passes)

As passagens para peixes por deflectores ou tipo Denil, consistem num canal rectilíneo de secção rectangular e de declive acentuado (12 a 50%), com deflectores dispostos ao longo do fundo e/ou nas paredes, com o objectivo de reduzir a velocidade média do escoamento (Larinier, 2002b). Os deflectores têm geralmente a forma de U e são dispostos com um ângulo de cerca de 45º contra a direcção do escoamento, originando correntes secundárias helicoidais que asseguram, por transferência de quantidade de movimento, uma eficiente dissipação de energia no seio do escoamento. O caudal requerido para funcionamento deste tipo de dispositivos é mais elevado do que qualquer outro tipo de passagens para peixes, pelo que apresenta um escoamento é caracterizado por elevada velocidade e turbulência, não devendo ser usada em situações de frequentes variações do nível de água a montante, visto ser pouco sensível a variações no nível de água a jusante. Apesar de formar bons caudais de atracção para os peixes, este tipo de passagem é extremamente selectivo, sendo apenas adequado a espécies dotadas de grande capacidade de natação, tanto em termos de velocidade como de resistência (ex. espécies salmonídeas). Pelo facto de não apresentar zonas de descanso para os peixes a sua travessia tem de ser feita de uma só vez, limitando igualmente a passagem dos peixes (Larinier, 2002d). As principais vantagens de utilização, incidem no pouco espaço requerido e os reduzidos encargos inerentes à sua construção. Este tipo de passagem é sobretudo adequado à transposição de obstáculos de pequena dimensão, em situações em que exista pouco espaço disponível. De acordo com o conhecimento actual, são relativamente selectivas, sendo pouco adequadas para espécies de menor capacidade natatória e menores dimensões, não permitindo a passagem de fauna bêntica (Baras *et a*l., 1994; Bunt *et al*., 1999; Bunt, 2001; Bunt *et al*., 2001).

Em Portugal foi construída uma passagem para peixes do tipo Denil, no açude do aproveitamento hidroeléctrico de Senhora do Salto, no rio Sousa, afluente da margem direita do rio Douro. Este dispositivo não foi considerado funcional por não ser adequado às espécies alvo, tendo sido substituído por um dispositivo com bacias sucessivas.

Passagens naturalizadas *"Close-to-nature types of structures"*

As passagens para peixes naturalizadas, constituem não só uma solução à transposição do obstáculo, mas próprias originam diferentes tipos de habitat propícios de utilização pelos peixes, de características semelhantes às encontradas em zonas de rápidos ou de pequenos cursos de água (FAO/DVWK, 2002). O tipo de material usado na construção deste tipo de passagem coincide com o existente no próprio local em condições naturais. A velocidade da água é relativamente baixa, sendo a energia dissipada pela turbulência gerada pela rugosidade do substrato do leito e das margens, bem como por uma série de expansões e contracções do escoamento devido à presença de blocos, calhaus e outro tipo de materiais, colocados de forma mais ou menos regular ao longo da passagem. a especificidade, característica deste tipo de passagens para peixes, implica a inexistência de critérios de dimensionamento definidos (Gebler, 1998). Não obstante ao que já referido, a utilização deste tipo de passagem apresenta ainda outras vantagens como: considerarem um maior número de requisitos biológicos, nomeadamente em relação à conectividade dos rios, do que as passagens tradicionais; o bom enquadramento paisagístico, consequente da utilização (sempre que possível) dos materiais de origem da zona de implantação; permitirem a passagem para ambos os sentidos, não só de espécies piscícolas mas como de outros elementos da fauna aquáticas, ex. macroinvertebrados

Inerentes á sua implantação, surgem igualmente aspectos menos favoráveis, destacando-se: a necessidade de espaço para o seu desenvolvimento, resultado do seu baixo declive (1% a 2%, máximo de 5%), em muitos casos limitação à sua aplicabilidade, o posicionamento muito a jusante da entrada da passagem relativamente ao obstáculo, resultante do baixo declive deste tipo de passagens o que pode restringir a sua eficácia e consequentemente tornando o uso bastante limitativo, particularmente em rios largos. Em rios de menor dimensão, esta desvantagem pode ser contornada, fazendo passar uma elevada proporção do escoamento, em períodos de caudais baixos, pela passagem. Por último, refere-se ainda sua quase inaplicabilidade em obstáculos de grande altura.

Seguidamente apresenta-se uma súmula das características funcionais dos tipos de passagens naturalizadas existentes:

Rampas e declives escavados *(Bottom ramps and slopes)*

Neste tipo de passagens toda a largura do rio é transformada numa superfície rugosa de pequena inclinação, resultado de uma suavização do gradiente hidráulico ao longo de um determinado troço da linha de água (FAO/DVWK 2002), permitindo a passagem, em ambas as direcções, por todo o tipo de fauna aquática (Harris et al. 1998).

Construção inicialmente direccionada à estabilização do leito dos rios, o inerente desenvolvimento ao longo de um perfil de suave inclinação e com elevada heterogeneidade de substrato grosseiro, favoreceu a existência de uma estrutura de habitats bastante diversa, que mimetiza as condições existentes associadas a um curso de rio naturalmente rico em diversidade estrutural, constituindo a alternativa mais vantajosa para a conectividade fluvial. Este tipo de passagem, é apropriada para situações de pequenos açudes, sem regularização do nível de água a montante, permitindo assim suavizar quedas de água bruscas inerentes a estes obstáculos, impeditivas à passagem dos peixes. A sua aplicação tem igualmente alguma utilidade como estrutura de protecção à erosão e de manutenção dos níveis de água a montante, mais ou menos constantes. Sob o ponto de vista ecológico, tem a vantagem de, a médio e longo prazo, permitir a "naturalização" da massa de água a montante do açude, através da remoção e arrastamento de materiais finos anteriormente acumulados. O seu enquadramento paisagístico, a pouca manutenção requerida, e a boa atractividade para os peixes ao longo de toda a largura do curso de água (FAO/DVWK 2002), são igualmente consideradas como vantagens inerentes à aplicabilidade deste tipo de passagens naturalizadas.

A distinção entre rampas e declives é baseada somente no declive das obras. As “rampas” são definidas como estruturas artificiais cujo declive de fundo varia entre 1:3 e 1:10, enquanto

Canais naturalizados (*Bypass channels*)

Um canal naturalizado consiste numa passagem que se desenvolve nos terrenos marginais ao curso de água principal, ao qual se une a montante e a jusante, contornando o obstáculo a transpor. Esta linha de água apresenta semelhante forma e função, a um canal lateral ou afluente natural do rio principal (Gebler, 1998; FAO/DVWK, 2002).

Este tipo de estrutura desempenha um papel essencial tanto para as espécies migradoras, como para as espécies reófilas, servindo não só de local de passagem mas também de habitat criado pelas mesmas (Aarestrup *et al.,* 2003; Eberstaller *et al.*, 1998; Mader *et al.*, 1998; Schmutz *et al.,* 1998). Este aspecto é particularmente importante para o caso de reabilitação de rios regularizados, em que as áreas de abrigo, alimentação e reprodução deste tipo de espécies são eventualmente escassas ou se encontram fortemente degradadas.

Podendo atingir grandes extensões, são geralmente adequados a todo o tipo de barreiras, desde que se verifique disponibilidade espacial para o seu desenvolvimento. Não são muito adequados para situações em que haja uma variação significativa dos níveis de água a montante, se bem que a construção de dispositivos de regulação do nível da água na entrada, pode atenuar esse problema. Além de se enquadrar harmoniosamente na paisagem, os custos de concepção são igualmente baixos, constituindo uma boa solução para corrigir a intransponibilidade de barreiras já existentes.

Rampas para peixes (*Fish ramps*)

Um açude apenas pode ser convertido numa rampa ou declive escavado ao longo de toda a sua largura, se não houver necessidade de controlo dos níveis da água e se existir um escoamento adequado para tal. No entanto, nem sempre essas condições se encontram disponíveis, pelo que se opta pela construção de uma rampa de largura não inferior a 0.20m (FAO/DVWK, 2002), integrada no próprio açude, formando um declive suavizado relativamente ao leito do rio (inferior a 1:20). Esta rampa, é revestida por uma superfície rugosa, geralmente substrato grosseiro, permite a redução da velocidade do escoamento facilitando migração da fauna aquática. A profundidade da água não deve exceder os 0.40me o caudal deve ter valores aproximados de 100l.s^{-1} (FAO/DVWK, 2002) .

Tal como nos outros dois tipos de passagens naturalizadas, um dos principais objectivos das rampas para peixes consiste na mimetização da variedade estrutural do leito de um curso de água natural.

São geralmente aplicáveis quando a altura a transpor é inferior a 3 m e, tal como os canais naturalizados, não são adequadas quando existem variações significativas do nível de água a montante, causadas por exemplo, por eventual presença de barragens.

A construção deste tipo de estruturas é tecnicamente exigente, uma vez que obriga a um elevado grau de estabilidade estrutural. Por outro lado, pode existir o risco de secarem em situações de caudais baixos, pelo que poderá ser necessário diminuir a permeabilização da base da estrutura. Apesar disto, requerem pouca manutenção e proporcionam geralmente um caudal de atracção adequado. Em termos de eficácia, são transponíveis por todo o tipo de fauna aquática, em ambas as direcções.

Passagens especiais *"Special constructions"*

Passagens para enguias *(Eel ladders)*

De uma forma geral, as passagens para enguias são pequenos canais revestidos de adaptações do tipo escovas ou camadas de mato e gravilha, atravessados por uma pequena lâmina de água, suficiente para permitir a passagem de enguias (Knight e White 1998). Uma outra alternativa é a existência de canos revestidos de pequenas escovas, mato, galhos ou gravetos, inseridos na própria estrutura do açude ("*eel pipes*"). Esta alternativa, contudo, não tem provado constituir uma solução eficaz, uma vez que têm uma tendência frequente a serem obstruídos, sendo igualmente de difícil manutenção. As passagens para enguias são geralmente usadas como circuitos secundários em passagens de bacias sucessivas com descarregadores de superfície e orifícios submersos, sendo somente necessárias em locais de ocorrência de migrações desta espécie. Por outro lado, não são estritamente necessárias, se a jusante do obstáculo já existe outra passagem para peixes. As vantagens deste tipo de estruturas é que apresentam um baixo custo de construção, necessitam de pouco espaço e de baixos escoamentos. No entanto, são apenas adequadas para enguias, não sendo por si só suficientes, para garantir a livre passagem das outras espécies piscícolas para montante.

Eclusas *(Fish locks)*

Contrariamente às restantes passagens para peixes (com excepção dos ascensores), as eclusas não proporcionam um caminho pelo qual os peixes se possam deslocar de forma a vencer o desnível, sendo a deslocação dos peixes para montante forçada através da elevação do nível da água no interior de uma conduta. Este tipo de dispositivo de passagem para peixes é constituído por uma conduta inclinada ou vertical e duas câmaras, uma posicionada a jusante do obstáculo, normalmente com maiores dimensões e outra a montante, cujo controle de entrada e saída de água é efectuado por meio de comportas de funcionamento automático operadas em função dos períodos de funcionamento da eclusa. (Travade e Larinier, 2002a; Clay, 1995). O principio de funcionamento de uma eclusa para peixes, que muito semelhante ao de uma eclusa de navegação, é composto pelas seguintes fases:

- Fase de atracção: a comporta de jusante encontra-se totalmente aberta e a comporta de montante controla o caudal que atravessa a eclusa; os peixes migradores são atraídos para a câmara de jusante pela corrente assim criada.

- Fase de enchimento: a comporta de jusante fecha-se e ocorre o enchimento da eclusa; os peixes migradores acompanham a subida do nível da água no interior da conduta e passam para a câmara de montante.

- Fase de saída: os peixes são estimulados a sair da eclusa para a albufeira através de uma corrente criada pela abertura de um “by-pass” na câmara de jusante.

- Fase de esvaziamento: a comporta de montante é fechada e esvazia-se lentamente a eclusa através do “by-pass” ainda aberto e, quando o nível de água na câmara de jusante é suficiente baixo, é aberta a comporta de jusante. O esvaziamento deve ser lento para evitar grandes velocidades e turbulências à entrada da eclusa, que possam repelir peixes que se encontrem nas proximidades da entrada.

O ciclo de funcionamento e a duração de cada uma das fases acima descritas é variável, sendo apenas durante a primeira fase, que o dispositivo exerce atracção sobre os peixes. Durante os períodos de enchimento, de saída dos peixes e de esvaziamento nenhuma atracção é exercida junto da entrada do dispositivo e qualquer peixe que se apresente nesta zona poderá abandoná-la antes que se inicie um novo período de atracção de peixes (Travade e Larinier, 2002b). Uma das desvantagens das eclusas incide no facto de durante a fase de saída, os peixes poderem entrar e sair ou permanecer na câmara de montante, voltando à câmara de jusante na fase de esvaziamento. Outra desvantagem incide na reduzida capacidade de passagem devido ao carácter descontínuo do seu funcionamento, bem como o curto período de tempo em que os peixes são atraídos. O seu planeamento e construção tecnicamente bastante exigentes, implicando elevados custos de construção, de manutenção e de funcionamento são igualmente factores limitantes à utilização destes dispositivos. Apresentam como vantagem permitirem vencer de desníveis elevados e em que o espaço e o escoamento disponível, são limitados.

Em Portugal existem 6 eclusas para peixes, nas barragens de Crestuma-Lever, Carrapatelo, Régua, Valeira e Pocinho, no rio Douro, e na barragem de Belver, no rio Tejo. Todas elas se mostraram pouco eficientes (Bochechas, 1995; Santo, 2005)**,** tendo sido postas fora de funcionamento as eclusas das barragens do rio Douro, com excepção da existente na barragem de Crestuma-Lever, devido à baixa eficácia dos dispositivos.

Ascensores *(Fish lifts)*

Os ascensores de peixes são dispositivos hidráulicos onde os peixes são atraídos pelo escoamento para a cuba, geralmente com uma entrada em forma de V (para impedir a saída dos mesmos), contendo água (2 a 4 m^3), que é posteriormente elevada através de um sistema mecânico, largando os peixes num canal ou directamente na albufeira (Travade *et al.*, 1992). Parente este mecanismo os peixes não efectuam nenhum esforço para vencer o desnível. À semelhança com as eclusas, o funcionamento deste dispositivo fcompreende então três fases: a fase de atracção, a fase ascensão e finalmente a fase de lançamento dos peixes a montante do obstáculo. A duração dos ciclos é regulada em função da quantidade de peixes potencialmente disposta a transpor o obstáculo em determinada época do ano (Barry e Kynard 1986; Bellariva e Belaud 1998; Kynard 1998; Travade *et al.* 1998).

Este tipo de passagens geralmente adaptado a estruturas de grandes dimensões (superiores a 15m) (FAO/DVWK 2002), requerendo pouco espaço disponível à sua instalação. São também caracterizados por se adaptarem bem aos obstáculos e serem independentes às variações do nível de água a montante (Travade e Larinier, 2002)**.** A sua principal desvantagem incide nos elevados custos de manutenção e funcionamento. Em Portugal, só se encontra em funcionamento um ascensor para peixes, na barragem de Touvedo, no rio Lima (Santo, 2005)**.** Este dispositivo foi monitorizado de Março de 1998 a Fevereiro de 1999, tendo sido observada a passagem de 1194 peixes, de sete espécies diferentes, concluindo-se que este dispositivo é relativamente eficiente (Santos *et al,* 2002).

1.8. POSICIONAMENTO DE UMA PASSAGEM PARA PEIXES E RESPECTIVOS FACTORES DE INFLUÊNCIA

A selecção do posicionamento de uma passagem para peixes é factor fundamental para sucesso de funcionamento da mesma. Este processo incide essencialmente na acessibilidade do dispositivo para efeitos de vigilância e manutenção e a sua atractividade para a fauna piscícola (Santo, 2005). Apesar de não interferir directamente no funcionamento do dispositivo, de facto, quer o posicionamento como a forma como a passagem se insere na infra-estrutura hidráulica, interfere acessibilidade à mesma, essencial ao seu controle e manutenção. Associada à eventual inacessibilidade ao dispositivo, surge a impossibilidade de detectar problemas e resolve-los, podendo limitar o funcionamento do mesmo. Relativamente à questão da atractividade, encontra-se directamente ligada à eficácia do dispositivo, dependendo essencialmente da localização e das condições hidrodinâmicas da entrada da passagem. Geralmente associada às migrações para montante, que geralmente dada a sua natureza activa, envolvem gastos energéticos na procura do caminho até chegar ao destino; a atractividade surge como factor determinante à condução dos peixes e à respectiva passagem para montante. Considerando que a totalidade da largura dos rios está geralmente disponível à migração dos peixes e que uma passagem para peixes representa apenas uma ínfima parte dessa secção, todo o processo de atractividade é por conseguinte complexo, envolvendo uma magnitude de variáveis a serem consideradas, destacando-se dentre as demais a velocidade de corrente, o caudal de escoamento e a localização da passagem. Esta última é considerada de importância critica, uma vez que o dimensionamento das passagens é geralmente limitado por diversos constrangimentos quer de índole hidráulica, engenheiral ou económicos; particularmente aquando da sua implantação em rios de grande dimensões (FAO/DVWK, 2002). Sendo a largura do curso de água muito superior à da entrada da passagem para peixes, a velocidade da corrente nas proximidade do obstáculo, surge assim como o único estimulo activo para o encaminhamento dos indivíduos até à entrada da mesma. Aquando do período de migração, o caudal de escoamento deverá encontrar-se entre aproximadamente 1 a 5% dos caudais de competição (Larinier, 2002c), devendo ser perceptível pelos peixes. A velocidade de corrente associada, é então indicador fundamental a todo este processo, devendo enquadrar-se dentro dos valores de referência para as diferentes espécies; na ordem dos 2-2.4 $m.s^{-1}$ para espécies salmonicolas e 1-1.5 $m.s^{-1}$ para espécies ciprinicolas.

Caracterizados pela sua capacidade reostática, os vertebrados aquáticos efectuam geralmente as suas migrações ao longo das zonas de corrente principal. Deste modo, para que facilmente detectáveis, as passagens para peixes deverão ser posicionadas junto às margens do rio, onde as velocidades de corrente são superiores. Assim, em rios de grandes dimensões poderá se justificar a implantação de dois dispositivos, um em cada margem do rio (Santo, 2005). Outro aspecto associado com o posicionamento das passagens diz respeito à sua protecção contra os caudais de cheia, os quais podem comprometer a estabilidade do dispositivo, nomeadamente nos casos das passagens por bacias sucessivas, cujos septos podem ser destruídos devido à força do escoamento.

A localização da entrada do dispositivo para a passagem dos peixes deverá situar-se o mais próximo possível do obstáculo a transpor, para que em caso de impedimento à sua progressão os peixes sejam impelidos a procurar uma passagem.

1.9. CRITÉRIOS DE DIMENSIONAMENTO DE PASSAGENS PARA PEIXES POR BACIAS SUCESSIVAS

Considerações gerais

O dimensionamento das passagens estabelece o funcionamento hidráulico das mesmas, que determina a eficiência de utilização pelos peixes. A conjugação entre factores de índole hidráulica e biológica, na concepção de uma passagem para peixes é por conseguinte essencial para garantir o bom funcionamento da mesma. Em termos gerais, as características especificas das espécies para as quais se destina a passagem, deverão ser consideradas, destacando de entre as demais: a capacidade de natação e de salto, a condição fisiológica dos espécimes, o seu tamanho e número. A consideração de tais características, resulta da necessidade de procurar minimizar o stress e tempo dispendido pelos peixes na transposição do obstáculo (Santo, 2005).

Dada à sua elevada representatividade em Portugal, apresentam-se seguidamente os critérios de dimensionamento base das passagens para peixes por bacias sucessivas. De uma forma geral, este tipo de passagens pode apresentar inúmeras variantes, as quais diferem essencialmente na forma como a água escoa de uma bacia para outra, resultantes das características dos septos e descarregadores utilizados (orifícios submersos, descarregadores de superfície ou fendas verticais)., cuja configuração e dimensionamento são passíveis de variação. Estas características geométricas, em conjunto com os níveis de água a montante e jusante da passagem, determinam o comportamento hidráulico na mesma, isto é, o caudal escoado, o desnível entre bacias consecutivas e o padrão de escoamento no interior da bacia (Larinier, 2002d), bem como os inerentes campos de velocidades e turbulência associados.

Seguidamente, apresenta-se uma detalhada descrição dos factores de dimensionamento hidráulicos considerados de maior relevância, a serem considerados aquando da concepção deste tipo de dispositivos hidráulicos:

Configuração e declive do canal

A configuração do canal incide primordialmente na disposição das bacias, que depende da sua inserção na infra-estrutura e na margem. A forma mais comum é a forma linear, na qual o escoamento se realiza essencialmente numa única direcção. Por vezes, por necessidade de adaptação às características da margem do rio ou mesmo por limitação espacial à construção da passagem para peixes, o canal pode apresentar inflexões ou as bacias podem ser dispostas lado a lado, sendo que nesta situação existe alteração do sentido do escoamento entre bacias (Santo, 2005).

O declive do canal depende do comprimento das bacias e do respectivo desnível entre elas, cuja relação estabelecida é expressa através da equação:

$$\text{Declive}= \Delta h/L \qquad (1.8)$$

onde, Δh é o desnível entre bacias e L o comprimento total da bacia. Deste modo para um mesmo desnível entre bacias o declive será maior quanto menor for o comprimento das bacias, enquanto que para um comprimento de bacias fixo o declive será maior para desníveis entre bacias mais elevados. Considerando a existência de valores limite para os parâmetros de dimensionamento das partes componentes de uma passagem para peixes, o declive do canal máximo passível de adoptar, resulta da conjugação de um volume máximo de bacia maximizado para um desnível de bacia mínimo (Santos, 2005).

Número e Dimensões das bacias

Na concepção de uma passagem para peixes, a definição do número e dimensionamento das bacias está intrinsecamente relacionado com as características biomecânicas e físicas das espécies piscicolas alvo. O número de bacias a comportar, depende do desnível a vencer e do desnível entre bacias, o qual por sua vez deve ser adequado às diferentes espécies em causa. É geralmente resultado do coeficiente entre o desnível a vencer e o desnível entre bacias, pelo que o número de bacias será maior quanto menor for o desnível entre bacias para um mesmo nível a vencer (Santo, 2005).

A definição do dimensionamento das bacias deverá ter como base as dimensões das espécies piscícolas bem como o seu comportamento migratório, proporcionando igualmente que a energia do escoamento seja dissipada com baixos níveis de turbulência mas com velocidade de escoamento não muito reduzidas (FAO/DVWK, 2002). A profundidade da bacia, deverá ser estipulado tendo em consideração as capacidades de salto das espécies, factor fundamental em dispositivos em que os peixes tenham que saltar aquando da sua transposição. As condições hidráulicas passíveis de ocorrer são igualmente factores determinantes ao delineamento das dimensões das bacias, sendo que a potência volumétrica dissipada por unidade de volume, indicador de turbulência, emerge como um dos principais aspectos a ser considerado. A potência volumétrica dissipada é inversamente proporcional ao volume de água existente na bacia, sendo definida como:

$$P_v = \frac{\rho g Q \Delta h}{LBh} \qquad (1.9)$$

onde ρ é a massa volumica da água (1000 Kg.m^{-3}), g a aceleração da gravidade (9.81 m.s^{-1}), Q o caudal de escoamento dentro passagem, Δh o desnível entre bacias, L o comprimento da bacia, B a largura da bacia e h a altura da água na bacia.

Os seus valores segundo Larinier (2002b), em passagens para peixes destinadas a espécies salmonídeas e ciprinícolas não devem exceder os 200 W.m^{-3} e 150 W.m-^{3}, respectivamente.

Desnível entre bacias

O desnível de uma bacia pode ser definido como a diferença de cotas altimétricas entre dois pontos equivalentes em duas bacias sucessivas (Santo, 2005). Este deve ser escolhido de acordo com as capacidades natatórias das espécies migratórias, sendo a progressão dos peixes para montante tanto mais facilitada quanto menor for o seu valor. No entanto, não deve ser adoptado um desnível demasiado reduzido por conduzir a um número de bacias excessivo (Larinier, 2002d). Segundo esta mesma perspectiva, valores de referencia foram estabelecidos para as diferentes espécies piscícolas, (Larinier, 2002b): Para espécies ciprinícolas o desnível entre bacias varia entre 0,15 e 0,25 m, sendo tanto menor quanto menor for o tamanho da espécie em questão**,** enquanto que para espécies salmonicolas os limites superiores indicados oscilam entre os 0.30 e os 0.60m, dependendo se são considerados, respectivamente, pequenos ou grandes salmonídeos

Dimensão das formas de comunicação entre bacias (Orifícios de fundo, descarregador de superfície e fendas verticais)

A largura mínima dos descarregadores de superfície e fendas verticais depende das espécies a que se destina a passagem para peixes, sendo de 0,30 a 0,40 m para salmonídeos, 0,45 m para sáveis e savelhas e 0,20 m para trutas. No caso da passagem para peixes se destinar a espécies ciprinícolas a largura mínima dos descarregadores e fendas depende do tamanho da espécie em questão (Larinier, 2002d).

No caso de orifícios de fundo, a sua largura deve ser suficiente (maior que 0,15-0,20 m) para evitar que fiquem facilmente obstruídos por detritos. Devem, também, ter uma área mínima de 0,09 a 0,10 m^2 quando a passagem se destina a espécies salmonídeas, e de 0,04 m^2 para trutas e para a maioria das espécies ciprinícolas (Larinier, 2002d).

Caudal de dimensionamento

O caudal de dimensionamento de uma passagem para peixes é um parâmetro de extrema importância pois influencia a atractividade da passagem para peixes, sendo esta tanto maior quanto maior o caudal escoado na passagem para peixes.

O valor do caudal de dimensionamento depende dos caudais que circulam no curso de água, no período de migração, adoptando-se, geralmente, valores de cerca de 1 a 5 % do caudal do curso de água nesse período. (Larinier, 2002c).

Para cursos de água onde circulam caudais elevados (caudal médio diário anual da ordem das centenas de m^3/s), dimensionar a passagem para peixes com um caudal tão elevado pode levar a custos proibitivos. Nestes casos, recorre-se à utilização de um caudal de atracção superior ao caudal de dimensionamento na extremidade de jusante da passagem, da ordem de 10% do caudal do rio na época de estiagem, e dimensiona-se a passagem para um caudal de cerca de 1 a 1,5% do caudal que circula no curso de água.

1.10. TÉCNICAS DE MONITORIZAÇÃO DAS PASSAGENS PARA PEIXES

A monitorização da eficácia e das condições de funcionamento de uma passagem para peixes é importante sob diversos pontos de vista: verificação da eficácia de novos dispositivos e eventual ajustamento das suas características, recolha de informação técnica e biológica indispensável ao dimensionamento e construção de futuros dispositivos e para uma gestão racional das espécies migradoras (Travade e Larinier, 2002).

As técnicas utilizadas incluem a monitorização do funcionamento hidráulico e mecânico do dispositivo, a recolha de informações biológicas indicadoras da eficácia do dispositivo, a contagem dos peixes que transitam pelo dispositivo e finalmente, a determinação da eficiência do dispositivo (relativização do número de passagens com a população migrante) (Travade e Larinier, 2002).

Monitorização do funcionamento hidráulico e mecânico

A monitorização do funcionamento hidráulico e mecânico consiste na medição e observação de determinados parâmetros e situações, que devem ser efectuadas imediatamente e periodicamente após a construção de um dispositivo, para verificar a conformidade deste com os critérios definidos em projecto.

Os parâmetros hidráulicos incluem a medição e conformidade dos níveis de água em locais específicos e nas proximidades do dispositivo, bem como nas quedas de água entre bacias e na entrada deste, no caso de passagens de bacias sucessivas com descarregadores de superfície e orifícios submersos. Incluem igualmente a verificação de que a estrutura dos escoamentos e o nível de turbulência em todo o dispositivo se mantêm compatíveis com as exigências das diversas espécies.

Os parâmetros mecânicos incluem a verificação periódica dos órgãos reguladores de caudal ou de nível ou dos mecanismos que asseguram o funcionamento das passagens ditas mecânicas, como as eclusas e ascensores.

É igualmente importante a verificação de eventuais obstruções por diversos tipos de materiais, tais como folhas, paus, troncos e pedras em determinados locais do dispositivo, particularmente nos orifícios submersos, que podem bloquear a passagem dos peixes, bem como reduzir o caudal de atracção.

Recolha de informação biológica qualitativa

Consiste na obtenção de forma indirecta de informação que se pode revelar extremamente útil numa análise qualitativa do funcionamento do dispositivo, nomeadamente: observação e/ou densidade (em caso de visibilidade) de peixes que tentam transpor o obstáculo, concentração de pescadores a jusante do obstáculo (sinal provável de ineficácia da passagem), observação de movimentos piscícolas ao longo do dispositivo, índices de abundância piscícola (por observação ou captura), observação de ninhos e locais de desova a montante do dispositivo.

Contagem de peixes

Captura

Este tipo de contagem de peixes consiste na captura destes num dispositivo instalado no interior ou à saída da passagem para peixes, e na sua contagem manual antes de os libertar a montante do obstáculo (Travade e Larinier, 2002). O dispositivo de captura é geralmente constituído por uma nassa em rede, com a entrada em forma cónica, o que facilita a sua retenção e posterior contagem a intervalos regulares. O seu dimensionamento deve ter em conta o número máximo de peixes que é possível coexistirem, devendo-se prever um volume de 10 l por quilograma de peixe (Clay 1995).

O sistema de contagem por captura é facilmente adaptável a dispositivos de pequenas dimensões, permitindo a fácil identificação das espécies, a aquisição de dados biométricos e a manipulação dos peixes para outros fins (marcação, repovoamentos). As desvantagens são um maior risco de ferimento nos peixes, maiores custos de manutenção e não permitir uma recolha contínua de dados (Travade, 1990).

Bloqueio

Este método consiste no bloqueio da saída da passagem para peixes por intermédio de uma rede ou grelha, com o objectivo de prevenir a entrada de peixes de montante. Seguidamente, os peixes são retirados da passagem por secagem desta ou por pesca eléctrica, sendo posteriormente feito um controlo do número de passagens provenientes de jusante. Este método é aplicável a todas as passagens que possuem zonas de descanso para os peixes, no entanto a sua aplicação pode facilitar a obstrução de orifícios submersos por folhas e diversos materiais.

Automática

O método da contagem automática consiste na utilização de dispositivos que reagem à passagem dos peixes, registando o número de passagens. Os contadores automáticos mais frequentes são *os de sonar*, em que a detecção é feita com base no eco de corrente da passagem do peixe através da zona de acção de uma sonda (Arnold, 1978); e *os de resistividade*, que se baseiam na diferença de condutividade entre a água e o corpo dos peixes (Bussel, 1978; Fewings, 1994). A vantagem da utilização deste tipo de contadores, é que exigem baixos custos de investimento e manutenção. A principal desvantagem é não permitirem a identificação das espécies, sendo por isso de aplicação restrita a rios com apenas uma ou duas espécies (truta e salmão). Recentemente foi desenvolvido por uma empresa islandesa (Vaki-Dng Ltd.) um contador de infravermelhos, o *Riverwatcher*, para contar e estimar o comprimento de indivíduos em passagens para peixes (Halfdanarson, 2001). Este dispositivo de monitorização funciona como um "*bio-scanner*", efectuando não só o registo do número de passagens e as condições em que estas se processaram (data, hora, sentido do movimento), mas também a gravação das silhuetas dos peixes e o registo de dados ambientais como a temperatura da água, num *software* informático compatível com o sistema operativo Windows 95 ou superiores. Encontra-se em utilização em diversos países, nomeadamente Noruega, Suécia, Finlândia, Islândia, EUA e Canadá, sendo sobretudo direccionado para a monitorização de salmonídeos. Em Portugal foi testado na passagem para peixes de Janeiro de Cima com resultados pouco satisfatórios (Pinheiro *et al.*, 2003).

Visual

A contagem visual é um método contínuo sem necessidade de manuseamento dos peixes e como tal, evita os principais inconvenientes da contagem por captura. O princípio consiste em obrigar os peixes a passar numa área em que são suficientemente visíveis para serem identificados e contados. Para tal existem duas técnicas: observação por cima, através da superfície da água, de uma zona pouco profunda, em cujo fundo é colocado um painel de cor clara; e observação lateral, através de uma janela vertical, onde os peixes são forçados a passar.

A contagem e a identificação podem ser efectuadas em tempo real, o que necessita da presença permanente de um observador. Esta solução não permite a aquisição simultânea de outros parâmetros (biometria, comportamento, etc.), apenas se justificando em dispositivos de grandes dimensões, em que as passagens são de funcionamento contínuo.

Os recentes progressos registados no campo da tecnologia de vídeo têm permitido maior automatização das operações e redução do tempo de contagem pelos observadores *in situ*. A monitorização das operações de contagem e identificação em passagens para peixes do tipo ascensor, são facilitadas pela natureza descontínua das passagens. Travade e Larinier (2002) citam o caso do ascensor de Poutès no rio Allier (França), em que apesar da observação por câmara de vídeo durante 24 h por dia, apenas são registadas imagens durante um curto período de passagem dos peixes, que corresponde a cada ciclo de elevação do ascensor. Esta solução permite assim reduzir o consumo de fita e o tempo de visionamento.

No entanto, na maioria das situações é necessário registar a imagem de uma forma contínua, dado que a passagem dos peixes pode ocorrer em qualquer momento. Existem dois métodos: i) gravação contínua de imagens a baixa velocidade e subsequente análise a velocidades superiores. As gravações de imagens são efectuadas de forma que uma cassete de vídeo de 3 h, possa durar 24 ou 48 h, ou seja a velocidade de gravação é reduzida para 1/8 ou 1/16 da velocidade normal. Contudo, a análise das cassetes pode tornar-se posteriormente um processo longo e penoso, se o número de peixes for significativo; ii) automatização de gravações apenas em sequências de imagens quando se encontram peixes em movimento em frente de uma janela de observação (sistema CERBERE). A utilização deste método reduz consideravelmente o tempo de gravação e, consequentemente, o tempo de visionamento. Além disso, os custos de operação são baixos, permitindo conhecer com grande rigor os períodos de migração e o comportamento das espécies. No entanto, a sua utilização é limitada em águas muito turvas.

Recentemente, foi desenvolvido um novo método que consiste na digitalização e gravação de imagens em ficheiros individuais, e posterior análise, utilizando um *software* adequado (Cattoen *et al.*, 1999). A principal vantagem desta metodologia é a redução significativa do tempo de visionamento e análise, comparativamente com o sistema CERBERE.

Determinação da eficiência do dispositivo

A eficiência de uma passagem para peixes é geralmente determinada em termos de proporção de indivíduos a jusante do obstáculo que conseguem efectivamente transpor o dispositivo, ou em termos de atrasos na migração. Existem dois tipos de métodos: métodos estatísticos e métodos de estudo comportamentais. Os primeiros constituem a metodologia mais directa e usual e consistem na medição ou estimativa do número total de indivíduos a jusante do obstáculo, por amostragens ou utilização de armadilhas, e posterior comparação com o número de efectivos que utilizou o dispositivo. Existem ainda alternativas indirectas que se baseiam na relação entre um número de indivíduos que são marcados a jusante do obstáculo e os que efectivamente usaram o dispositivo, incorporando ainda um coeficiente ($0< C <1$) que representa a influência das operações de marcação nos peixes. Em termos práticos, a maior dificuldade consiste na estimativa desse coeficiente, uma vez que a referida influência pode ser insignificante em algumas espécies (salmonídeos) ou induzir alterações de comportamento ou mesmo morte, noutras (sável) (Travade e Larinier, 2002).

Os métodos de estudo comportamentais têm como objectivo evidenciar os factores que influenciam a eficiência de uma passagem para peixes, tais como a localização da respectiva entrada, o escoamento no dispositivo e o efeito de determinados factores ambientais.

Envolvem a monitorização directa do movimento e comportamento dos indivíduos, particularmente durante a sua aproximação ao dispositivo. As técnicas de telemetria, baseadas na detecção remota de um sinal, emitido através de transmissores colocados nos indivíduos a monitorizar, têm sido as mais usadas (Travade e Larinier, 2002). As vantagens desta metodologia traduzem-se pela monitorização dos indivíduos marcados ser efectuada no habitat natural, a perturbação ser mínima, desde que a captura e posterior instalação dos transmissores seja efectuada correctamente, ser uma técnica adequada para situações de fraca ou nula visibilidade e permitir realizar estudos de grande amplitude, como por exemplo, no caso das migrações transcontinentais. Apresenta no entanto como principais desvantagens, o elevado custo do material utilizado, sobretudo transmissores ("*tags*") e receptor ("*data logger*") e ainda ser limitativa para espécies/indivíduos de pequena dimensão, nomeadamente nos casos em que o peso do transmissor exceda 2% do peso corporal dos peixes a monitorizar (Brown *et al.*, 1999).

Actualmente existem três sistemas de telemetria: ultra-sónico, radio-telemetria e satélite. Em ambientes dulçaquícolcas, o sistema de radio-telemetria tem sido, ao longo das últimas décadas, a técnica mais aplicada na monitorização de migradores (Chanseau e Larinier, 1999; Chanseau *et al.*, 1999; Travade e Larinier, 2002b). Este sistema utiliza transmissores que emitem em bandas compreendidas entre 20 e 180 MHz, permitindo uma maior facilidade na detecção de sinais na água, podendo atingir distâncias relativamente longas, até 2 km (Travade e Larinier, 2002b). Apresenta ainda a vantagem, em relação aos outros de sistemas de telemetria, de ser menos perturbado pelos ruídos existentes nos cursos de águas e pelos emitidos por centrais hidroeléctricas (Travade e Larinier, 2002b).

1.11.OBJECTIVOS E ESTRUTURA DA DISSERTAÇÃO

Face ao exposto, e atendendo às insuficiências de informação indicadas, a presente dissertação teve como principal objectivo o aumento dos conhecimentos sobre o comportamento do barbo Ibérico e dos respectivos requerimentos biológicos e hidráulicos associados à utilização de uma passagem para peixes por bacias sucessivas na sua movimentação para montante. Os resultados obtidos pretenderam fornecer informação para o delineamento de critérios óptimos de dimensionamento adequados a esta e outras espécies de características biomecânicas semelhantes. O estudo da eficiência de diferentes configurações hidráulicas num protótipo experimental de uma passagem para peixes por bacias sucessivas à passagem para montante de espécimes de diferentes classes de dimensão foi deste modo realizado.

No âmbito do objectivo principal deste estudo, a dissertação foi estruturada em seis capítulos. No primeiro capítulo, referente à presente introdução geral, efectua-se o enquadramento geral deste estudo, sendo demonstrado a importância do mesmo, bem como a definição dos respectivos objectivos e sua estruturação. Os subsequentes quatro capítulos apresentam o trabalho experimental efectuado e os resultados obtidos, visando os seguintes objectivos específicos: Capitulo 2 - estudar a eficiência de passagem por orifícios submersos ou descarregadores de superfície à passagem do barbo ibérico aquando da transposição entre bacias sucessivas. Analisar a existência de diferenças em termos de utilização preferencial deste tipo de passagens entre peixes de duas classes de dimensões distintas. Capitulo 3 - investigar o efeito da velocidade, turbulência e tensões de Reynolds, no comportamento desta espécie, e definir quais as variáveis hidráulicas que mais influenciam o comportamento dos peixes. Análise de possíveis diferença nas respostas comportamentais dos espécimes de diferentes dimensões face a estas variáveis. Capitulo 4 - avaliar a adequabilidade de orifícios desalinhados e alinhados à passagem para montante de espécimes de diferentes dimensões. Caracterizar as condições hidráulicas existentes em ambas as configurações, com vista a compreender comportamento dos peixes aquando a sua passagem para montante. Capitulo 5- avaliar a eficiência de orifícios desalinhados e alinhados com uma barra deflectora à movimentação para montante dos espécimes. Estudar a analisar as características hidráulicas inerentes a ambas as configurações, visando o entendimento entre a relação estabelecida entre as mesmas e a movimentação dos peixes. O último capítulo, Capitulo 6, apresenta uma súmula dos principais resultados obtidos, das suas implicações e das subsequentes necessidades de investigação futura que suscitam. Os quatro capítulos base que compõem a dissertação são apresentados sob a forma de artigos científicos, publicados, aceites ou submetidos para publicação em revistas de índole cientifico de reconhecimento internacional, encontrando-se por esse motivo na Língua Inglesa, em conformidade com a forma original submetida para publicação. Esta estratégia é de salutar devido ao facto de a Língua Inglesa ser cada vez mais a forma universal de expressão nos meios científicos, favorecendo à maior divulgação do trabalho realizado. No entanto, algumas desvantagens que advém desta estratégia são igualmente notórias, salientando-se a repetição de aspectos metodológicos quando se comparam os diferentes capítulos entre si.

Os capítulos/artigos apresentados são os seguintes:

Capítulo 2 – Silva AT, Santos JM, Franco AC, Ferreira MT, Pinheiro AN.2009. Selection of Iberian barbel *Barbus bocagei* (Steindachner, 1864) for orifices and notches upon different hydraulic configurations in an experimental pool-type fishway. *Journal of Applied. Ichthylogy.* **25**: 173– 17.

Capítulo 3 – Silva AT, Santos JM, Ferreira MT, Pinheiro AN, Katopodis C. (*sob revisão*). Effects of water velocity and turbulence on the behaviour of Iberian barbel (*Luciobarbus bocagei* Steindachner 1865) in an experimental pool-type fishway. *River Research and Applications.*

Capítulo 4 – Silva AT, Santos JM, Ferreira MT, Pinheiro AN, Katopodis C. (*submetido*). Iberian barbel (*Luciobarbus bocage*i Steindachner 1865), preference for straight or offset orifices in an experimental pool-type fishway. *Journal of Hydraulic Research.*

Capítulo 5 – Silva AT, Santos JM, Ferreira MT, Pinheiro AN. (*submetido*). Study of the efficiency of a new design of pool-type fishway for the Iberian barbel (*Luciobarbus bocage*i Steindachner 1865). *Ecological Engineering.*

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2. SELECTION OF IBERIAN BARBEL *BARBUS BOCAGEI* (STEINDACHNER, 1864) FOR ORIFICES AND NOTCHES UPON DIFFERENT HYDRAULIC CONFIGURATIONS IN AN EXPERIMENTAL POOL-TYPE FISHWAY[1]

ABSTRACT

Trends in fish passage studies are increasingly moving towards a holistic approach considering movements of a wide range of species and other aquatic fauna. In this context, it is important to consider not only salmonids and other game species, but also coarse species, such as cyprinids. Moreover, knowledge on their behaviour when facing fishways, particularly their upstream movements upon different hydraulic configurations, is still scarce and poor. To address this lack of knowledge, this study presents results from an experimental research conducted in an indoor real scale pool-type fishway to assess how a cyprinid species, the Iberian barbel *Barbus bocagei* (Steindachner, 1864), responded to the simultaneous presence of submerged orifices and surface notches, with adjustable dimensions, in association with two different flow regimes over the notches, i.e. plunging and streaming. Overall, there was a clear selection for orifices (76%) to negotiate the fishway. A significantly higher proportion of individuals selected the orifices to move upstream when the flow was on the plunging mode, but proportions were equivalent during streaming flow conditions. Time taken for fish to enter the fishway differed significantly according to the discharge device chosen and was lower for submerged orifices (52 s – 35 min.). The present study identified key factors on Iberian barbel upstream movements that have direct applications to future fishway design for this species.

KEY WORDS: fish passage; pool-type fishway; *Barbus bocagei*; passage type.

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[1] Based on paper: Silva AT, Santos JM, Franco AC, Ferreira MT, Pinheiro AN.2009. Selection of Iberian barbel *Barbus bocagei* (Steindachner, 1864) for orifices and notches upon different hydraulic configurations in an experimental pool-type fishway. *Journal of Applied. Ichthylogy.* **25**: 173–17

2.1. INTRODUCTION

River fragmentation by dams and weirs has been identified as one of the most dramatic impacts of human societies on stream fishes, particularly for those that perform migrations within the river systems (Lucas and Baras, 2001). The continuous decline of many species stocks stimulated the development of the so-called "fishways", which are of increasing importance for the restoration of free passage for migratory fish in rivers (Clay, 1995). However, the restoration of fish passage has historically focused on anadromous species with high commercial value (Laine et al., 2002), with low emphasis being given to coarse species. Recent studies demonstrated that these fishes may migrate over long distances to reach their spawning grounds or for refuge and trophic reasons (Ovidio and Philippart, 2002). Moreover, knowledge on their migratory behaviour and swimming capabilities is generally poor and scarce (Santos et al., 2005). Therefore, to provide fish passage towards the restoration of stream connectivity, studies accommodating movements and behaviour of coarse fish, such as cyprinids, are becoming increasingly necessary for future fishway design. This challenge is highlighted in Iberian rivers where cyprinid fishes are frequently the most dominant and abundant group of species encountered (Doadrio, 2001). The main fishway options for those fishes at low weirs, which stand as the most common stream barriers are the pool-type fishways (Santos et al., 2006). It consists of a series of pools separated by cross-walls with submerged orifices at the bottom and/or surface notches, arranged in a stepped pattern. Fish may move from pool to pool by leaping over the notches or swimming through submerged orifices.

The Iberian barbel *Barbus bocagei* (Steindachner, 1864) is one of the most common cyprinid species in Iberian rivers. Though their migration and feeding ecology have been assessed in recent studies (Collares-Pereira et al., 1996; Santos et al., 2005), little is known about their behaviour when facing pool-type fishways, particularly whether they negotiate them by swimming through submerged orifices or leaping over the surface notches. This information is needed to develop robust general guidelines for future fishway designs. However, to be successful, studies should be based on balanced experimental designs, in which the variables of interest can be manipulated while controlling for confound effects. Studies conducted on such conditions offer an excellent opportunity to gain generic insights into fish behaviour.

The primary goal of this study is to assess, under the experimental conditions of a indoor real-scale pool-type fishway, the behavioural response of Iberian barbel to different hydraulic configurations. Specifically, the following questions were asked: (a) do Iberian barbel prefer to swim through submerged orifices or over the surface notches?; (b) are the proportions equivalent of Iberian barbel that passed through the orifices and notches upon different notch dimension and flow regimes over the notches?; (c) do Iberian barbel take the same time to enter the fishway by using submerged orifices or surface notches; and (d) is there a relation between passage time through orifices/weirs and flow discharge?

2.2. MATERIALS AND METHODS

Fishway facility

The experimental study was conducted in an indoor real scale pool-type fishway located at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), Lisbon. The structure was 10 m long, 1 m wide and 1.2 m high, and presented a steel frame, with glass-viewing panels on both sidewalls (Figure 2.1). It consisted of 6 pools (1.9 m long x 1.0 m wide x 1.2 m high) divided by five cross-walls, each one incorporating a submerged orifice and a surface notch of adjustable width on opposite sides creating a sinusoidal flow path. The fishway was positioned at a slope of 8.5%, which is within the range of those commonly used in this type of fishways (Larinier, 2008). The fishway also encompassed an acclimation chamber (4.0 x 4.0 x 3.0 m) at the downstream end of the channel, which was separated from the main structure by two mesh panels. Two slot gates, positioned at the upstream and downstream ends of the fishway were used to control the discharge and the water level within the structure, respectively. Water used in the experiments was drawn from domestic water supply (soft water) and was recirculated through the system for at least two weeks prior to the experiments to ensure throughout dechlorination and “maturation” (Copp et al., 1998), and checked for temperature, hardness, pH and dissolved oxygen at the beginning and at the end of experiments by means of a multiparametric probe (Hydrolab, Quanta model).

Fish capture and holding

Iberian barbel were collected from the River Sorraia, the largest left tributary of the River Tagus, central Portugal. Further details of the sampling area may be seen in Collares-Pereira et al. (1995). Sampling was undertaken using electrofishing (Electracatch International, SAREL model WFC7_HV, Wolverhampton, UK) with low voltage (250 V) and a 30 cm diameter anode to reduce the effects of positive galvanotaxis. Fish were captured during a natural reproductive migration, which generally takes place from April-June (Santos et al., 2005). Fish were all mature as shown by in situ macroscopic observations of their gonads development stage, particularly their volume, vascular irrigation and visibility of oocytes, and by the presence of nuptial tubercles (Agostinho et al., 2007). A total of 45 Iberian barbel of *ca.* 14.0-28.5 cm total length (TL) were brought to the laboratory facilities and randomly introduced in three 1.45 x 0.70 x 0.80 m tanks equipped with ELITE aerator systems, at a number of 15 individuals per tank. Fish size was similar among the tanks (mean total length (TL) ± SD: A = 18.6 ± 3.1 cm, B = 20.7 ± 2.4 cm, C = 19.6 ± 3.1 cm; ANOVA, F = 2.13, df = 2, $P > 0.05$), which allowed for valid comparisons to be made between experiments. The laboratory was well lit with natural light. Difference in water temperature between the collection site and the tanks / fishway (mean temperature = 18ºC) was less than 2ºC. Fish were kept in the tanks for 1-2 weeks before experiments started. During that period, the water was permanently filtered by a mechanical filter and a closed circuit with a turn over rate of 200 l per day. Feeding was supplied as pond sticks (Tetra Pond) three times a week, but stopped 24 h prior to experimentation.

Experiments

Each experiment took place on a different day (28 April - 10 May 2005) and was performed between 17:00h-22:00h, to encourage attempts by this species which typically migrates at dusk (Santos et al., 2005). The submerged orifices dimensions (width × height) were set at 0.20 x 0.20 m and remained constant throughout the study period. These dimensions have been found to be adequate for upstream passage of other European cyprinid species in pool-type fishways (Larinier, 2002), but their adequability to the target species remains still unknown. Parallelly, a design consisting of combinations of two different surface notch dimensions (width × height) – 0.20 x 0.30 m and 0.30 x 0.30 m – with two different flow regimes over the notches - plunging and streaming (Rajaratnam and Katopodis, 1988) - was employed to test the ability of Iberian barbel to negotiate with different hydraulic configurations. These dimensions were previously determined from calculations to approximately match velocities between the two pass openings. Accordingly, mean velocity through the orifices was determined considering head drop between consecutive pools and the discharge coefficient of a square orifice with jet contraction in two of the edges, whereas velocity through the notches was calculated by the quotient between notch discharge and the flow cross section on the plane of the crest. The flow height at this cross section was measured through a transparent scale attached to the side wall. Overall, three replicates (A, B and C) of each hydraulic configuration (notch width x flow regime) were tested, giving a total of 4 experiments (Table 2.1). Each replicate used individuals of a different tank, which were allowed to recover for 48 hours, prior to the beginning of the next experiment. Discharge (*Q*) was fixed among replicates and previously determined to create a head drop between the pools of 0.16 m - producing a maximum flow velocity of ≈ $\sqrt{2g\Delta h}$ = 1.77 m s^{-1}, where g is the acceleration due to gravity, 9.8 m s^{-2}, and Δh is the head drop between two consecutive pools - and a turbulence not higher than 100 W m^{-3} in all experiments. These values fall within the range of recommended ones for pool-type fishways when cyprinids are the target species to be passed (Larinier, 2002). Individuals of each tank were first introduced into the downstream chamber and provided with a 12-h acclimation period. Fish behaviour, whether moving through submerged orifices or over the surface notches, was continuously monitored through the glass sidewalls of the fishway by means of direct observation and video recording. A fish was considered to perform a successful upstream passage when the total of its body length was within the following pool. Direct observations were performed during the whole time of an experiment (*c*. 5 h) and were made at approximately 1 m distance from the channel, approaching and leaving discreetly the observations points, respectively before and after each experiment. This caused no disturbance to the fish, as revealed by a previous pilot study (unpublished data). Observations were also supplemented by four video cameras (Panasonic, WV-BP100 model), connected to two time-lapse video recorders (Panasonic, AG-6720A model), positioned at the two uppermost cross-walls and focused particularly on both openings. Five 175 W infrared lamps fixed above the fishway and programmed to be turned on from 20:30-22:00 h, allowed the observation procedures when natural light was no longer sufficient to monitor fish movements. These lamps have been used in other fishway studies (e.g. Santos et al., 2005) and their presence had no effect on fish behaviour.

Data analysis

Non-parametric Mann-Whitney U-tests (Zar, 1996) were used to test the null hypothesis that (i) the proportion of fish that moved through the submerged orifices was equivalent to the proportion of fish that passed over the surface notches; (ii) the proportion of fish that passed through the submerged orifices and surface notches was equivalent for both notch widths tested (0.20 m and 0.30 m). For this analysis data were pooled over different flow regimes to increase statistical power; (iii) the proportion of fish that passed through the submerged orifices and surface notches was equivalent for both flow regimes (plunging and streaming) occurring over the notches (data pooled over different notch widths) and (iv) the time taken for fish to enter the fishway by using the submerged orifices was equivalent to the time taken for fish to enter the fishway by passing over the surface notches. Correlations between discharge and passage time through orifice and notches were further analysed using the Spearman rank statistic.

2.3. RESULTS

All fish successfully ascended the fishway during the four experiments, though the number of passages through the orifices and notches was statistically unequal. Overall, a much higher number of passages through the submerged orifices (1781, 76%) were registered by fish during their upstream movements within the fishway, relatively to those that occurred over the notches (Mann-Whitney U-test, $Z = -3.52$, $P < 0.05$) (Table 2.1). A higher number of upstream movements through submerged orifices and surface notches were observed when notch width was set at 0.30 m (1376, 59%) relatively to 0.20 m, but this was not statistically significant (Mann-Whitney U-tests, $P > 0.05$). Experiments conducted during plunging flow conditions revealed an unequal proportion of individuals selecting the orifices and notches, with a higher proportion using the former (Mann-Whitney U-test, $Z = -2.84$, $P < 0.05$). Contrarily, fish were likely to display a higher use of the notches for streaming flows relatively to plunging flows, as during the former no significant differences were found in the number of individuals that passed through the orifices and over the notches (Mann-Whitney U-test, $Z = -1.21$, $P > 0.05$). The time taken for fish to enter the fishway after they were introduced in the acclimation chamber differed significantly upon selection of orifice or notch (Mann-Whitney U-test, $Z = 3.46$, $P < 0.05$). Iberian barbel that selected the submerged orifice took between 52 s and 35 min. to pass, whereas the time taken to pass over the surface notch varied between 25 min. and 3 h. There was no relation between discharge and passage time through the submerged orifices (Spearman rank correlation, $r = 0.17$, $P > 0.05$), however a significant pattern (i.e. higher number of passages observed on lower discharge events) was encountered when movements took place over the notches (Spearman rank correlation, $r = -0.60$, $P < 0.05$).

2.4. DISCUSSION

When fish are being tested in a fishway with the goal of assessing their behaviour, in particular their upstream movements upon different hydraulic configurations, it is important that fish are in appropriate physiological state to be motivated to swim upstream. In the present study, a sound indication that this motivation was present was that all individuals ascended the fishway in response to every flow discharges without the need to be forced through. Moreover, continuous observation on fish movements did not report any unnatural behaviour caused by operational procedures. Gas oversaturation due to pumping water was unlikely to occur, as typical related symptoms, such as heavy gasping or bubbles / blisters around the head and eyes of fishes were not found throughout the experiments (Bouck, 1980). Similarly, gasping or presence of darkened gills, symptoms of an excess carbon dioxide on the water, was not registered at all during the study.

The design of the experimental study was well balanced in terms of hydraulics because velocities were similar between the orifices and notches among all experiments. Under these conditions, a significant proportion of upstream movements were found to occur through the submerged orifices. This result has also been noted for brown trout (*Salmo trutta* L.) and Atlantic salmon (*Salmo salar* L.) in a similar experimental design study (Guiny et al., 2003). Though velocities were similar between both fish pass openings, it is possible that flow from the submerged orifice may have provided a more directional stronger cue to approaching fish. Future studies should consider using advanced techniques such as the ADV (Acoustic Dopler Velocimeter) to characterize the velocity components (x, y, z) of flowing water, in a tentative to further clarify the mechanisms responsible for the choice of different fishway openings.

The type of flow regime over the notches also appeared to play an important role in the upstream movements of fish. In fact, a significant higher proportion of individuals selected the submerged orifices to pass rather than surface notches, when the flow was on the plunging mode. In a similar study using Atlantic salmon as the target species, Stuart (1962) found an opposite pattern when analysing their upstream movements within an experimental pool-type fishway. We attribute this low proportion of individuals using the surface notches at plunging flows to limitations in the swimming ability of this species (Doadrio, 2001). The repeated use of the same fish could also have lowered their swimming performance on subsequent experiments due to lactate production caused by burst activity in a tentative to leap over the plunging flow. This re-use of fish, although not statistically desirable, may in fact provide a more realistic indication of the potential ability of Iberian barbel to use orifices and notches in real pool-type fishways. Learning of flow patterns has been suggested as an explanation of improvements in fish movement through experimental fishways (Laine, 1990). Nevertheless, at the present study, the recovery period of 48 h prior to beginning of the next experiment should have been sufficient for the fish to metabolize any lactate (Wardle, 1978). Contrarily, during streaming flow conditions, the presence of a continuous surface stream flowing over the crest of the notches would require Iberian barbel a lower effort, by allowing individuals to swim over the notches instead of leap over them, hence the observed similar proportion of fish using both fish pass openings. The use of recent techniques to monitor intensity of fish activity, such as electromyogram telemetry in association with numerical flow simulations, remains a promising option to further clarify species behavioural patterns during obstacle negotiation upon different types of flow regimes.

Time for fish to pass over the surface notch was significantly higher than in the case of passage through the submerged orifice. As fish were offered similar velocities at both pass openings in all experiments, they should choose the path that would tend to minimise energy expenditure and risk of predation while accounting by a need to make a rapid upstream progress to increase the chances of spawning (Hinch and Rand, 2000). Swimming through the submerged orifice, fish should have had the chance to avoid the jet core (the central focus of highest velocities) by negotiating close to the edges, a situation that could be easily confirmed during in situ and video observations. Though there is no data on velocity components (x, y, z) measured at the different horizontal layers in the vicinity of the cross-walls to support our hypothesis, it is believed that some of the variation in passage time might be related to environmental variables, but the experiments were not designed to test this possibility.

The results of this study may have important implications to the design of fishways for Iberian barbel. Accordingly, submerged orifices are likely to be a better option than surface notches for upstream passage of Iberian barbel. However, scientists and technicians should be aware of the possible presence on the site of debris loads and fine elements that could easily obstruct the orifices, thereby limiting fish movements. Additional maintenance may therefore be required on such cases. Nevertheless, if surface notches are provided and sufficient water is available, streaming flow conditions should be encouraged in detriment of plunging flows. This could be easily achieved by increasing the fishway discharge and allowing submersion of the crest of the notches as a consequence of increase in the water level of the downstream pools. Fish would then be able to swim over the obstacles instead of leap over it. There are, however limits to the application of our results. Some natural pool-type fishways may have roughness elements, such as large bottom substrates or logs that can be used by the fish to assist their upstream movements or to hold their position before a subsequent effort (Larinier, 2008). In other situations, the presence of such structures may result in complicated flow phenomena, such as turbulent jets and eddy formation that may hinder these behaviours (Clay, 1995). As the study was developed in a pool-type fishway with smooth walls and floor, the occurrence of such phenomena was null or, at least, had no significant expression, as all fish did not show sign of disorientation and could successfully ascend the pass during all experiments. Thus, these results should be applied to those situations that are hydraulically similar to the laboratory experimental conditions.

Although some authors argue that experimental laboratory research on fishways cannot replace studies conducted in the field (Lobón-Cervia et al., 2003), a fully comprehensive approach to understand the influence of fish behaviour on passage success requires the integration of research conducted over different scales. The present study provided evidence of specific behaviour of Iberian barbel using orifices and notches in response to different hydraulic configurations in an experimental pool-type fishway and suggests that studies conducted on similar conditions may provide useful insights necessary to improve fish passage. Further research, combining both field and laboratory investigations are needed to provide a deeper understanding of the influence of fish behaviour on passage success, namely their physiological response to different hydraulic scenarios.

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Table 2.1. Experimental conditions tested in an indoor real scale pool-type fishway to study the behaviour of Iberian barbel. Mean total length (TL) ± standard deviation (SD) of individuals is also given.

Experiments	Replicate	Q ($l.s^{-1}$)	Notch width (m)	Flow regime	Mean velocity ($m.s^{-1}$)		Water temperature (ºC)	Mean TL ± SD (cm)
					orifices	notches		
1	A	70.6	0.20	plunging	1.14	1.07	18.3	18.6 ± 3.1
1	B	70.6	0.20	plunging	1.14	1.07	18.3	20.1 ± 2.4
1	C	70.6	0.20	plunging	1.14	1.07	18.3	19.7 ± 3.1
2	A	90.3	0.20	streaming	1.14	1.10	18.0	18.6 ± 3.1
2	B	90.3	0.20	streaming	1.14	1.10	18.0	20.1 ± 2.4
2	C	90.3	0.20	streaming	1.14	1.10	18.0	19.7 ± 3.1
3	A	83.2	0.30	plunging	1.14	0.96	18.2	18.6 ± 3.1
3	B	83.2	0.30	plunging	1.14	0.96	18.2	20.1 ± 2.4
3	C	83.2	0.30	plunging	1.14	0.96	18.2	19.7 ± 3.1
4	A	108.3	0.30	streaming	1.14	1.01	18.0	18.6 ± 3.1
4	B	108.3	0.30	streaming	1.14	1.01	18.0	20.1 ± 2.4
4	C	108.3	0.30	streaming	1.14	1.01	18.0	19.7 ± 3.1

Table 2.2. Number of passages through the submerged orifices and surface notches observed during the experimental conditions tested in an indoor real scale pool-type fishway to study the behaviour of Iberian barbel.

Experiment	Notch width (m)	Flow regime	Number of passages		
			Submerged orifice	Surface notches	Total
1	0.20	plunging	413	792	492
2	0.20	streaming	354	118	472
3	0.30	plunging	601	98	699
4	0.30	streaming	413	264	677
Total			1781	559	2340

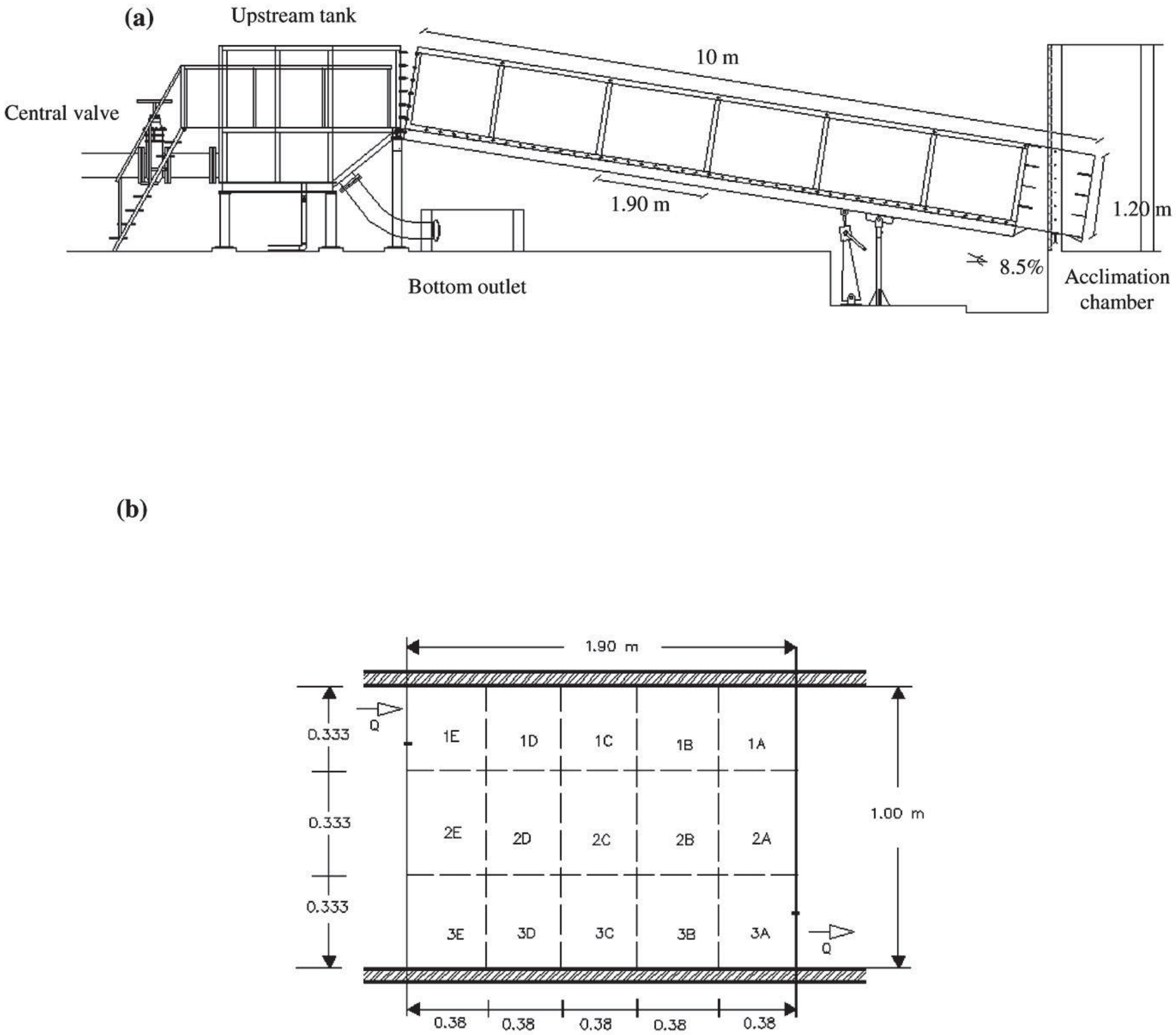

Fig. 2.1. (a) Side view of the artificial real scale pool-type fishway at the National Laboratory for Civil Engineering; (b) details of a cross-wall showing the submerged orifice and the surface notch.

3. EFFECTS OF WATER VELOCITY AND TURBULENCE ON THE BEHAVIOUR OF IBERIAN BARBEL (*LUCIOBARBUS BOCAGEI*, STEINDACHNER 1865) IN AN EXPERIMENTAL POOL-TYPE FISHWAY[2]

ABSTRACT

The restoration of fish passage has been focused on anadromous fish species, whilst studies accommodating passage of coarse species have often been considered incidental, yet frequently these are the predominant group of species encountered in rivers. In addition, fishway designs depend greatly on the interplay between hydraulics and biomechanics, yet very little data are available on the responses to specific hydraulic settings for these species. This study aims to explore the effects of water velocity and turbulence on the behaviour of a cyprinid species - the Iberian barbel *Luciobarbus bocagei* (Steindachner, 1864) - particularly their upstream movements upon different discharges (38.5 to 77.0 $l.s^{-1}$), through an indoor full scale pool-type fishway prototype. Larger adults had a higher passage success (mean = 79 %) and took less time (mean ± SD (min): 5.7 ± 1.3) to negotiate the entire 6 pool fishway, when compared to small adults. Correlation analysis between hydraulic variables and fish transit time yielded different results. Correlations were found to be the highest between the horizontal component of Reynolds shear stress and fish transit time, particularly for smaller size-individuals ($r = -0.45$; $p < 0.001$), highlighting this variable as a key-parameter which strongly determines the movements of Iberian barbel. The present study identified key factors on Iberian barbel movements that may have direct application to future fishway designs for this species and for other "weak" swimmers.

KEY WORDS: Cyprinids, Fish pass, Fishway, Kinetic energy, Reynold's shears stress, Acoustic Doppler Velocimeter.

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[2] Based on paper: Silva AT, Santos JM, Ferreira MT, Pinheiro AN, Katopodis C. (*under review*). Effects of water velocity and turbulence on the behaviour of Iberian barbel (*Luciobarbus bocagei* Steindachner 1865) in an experimental pool-type fishway. *River Research and Applications.*

3.1. INTRODUCTION

River fragmentation by dams and weirs is one of the major causes for the dramatic decline in the range and abundance of freshwater fish (Lucas and Frear, 1997; Cowx and Welcomme, 1998; Lucas and Baras, 2001), particularly on those that complete their migrations within river systems (Nicola *et al.*, 1996; Poulet, 2007). In order to minimize such consequences on riverine communities, considerable effort has been devoted to the development of the so-called “fishways” which are of increasing importance for the restoration of passage for migratory fish in rivers (Clay, 1995; FAO/DVWK, 2002; Katopodis 2005). Biologically oriented fishway research has focused mostly on anadromous fish species (e.g. salmonids) (Bunt *et al.* 1999; Baras *et al.*, 1994; Laine *et al.*, 2002; Gowans *et al.*, 2003; Katopodis, 2005). Therefore, considerably limited information on coarse species has been available, particularly on cyprinids. Recent studies have proven that these species can travel considerable distances for reproduction, refuge and feeding purposes (Lucas and Frear, 1997; Ovidio and Philippart, 2002; Katopodis, 2005). Therefore, there is an increasing need to conduct studies to accommodate movements and behaviour of coarse fish within fishways and to assess the effect of potential key-variables that should be considered for the successful development of future designs.

In Portugal, the most common fish pass is the pool-type fishway (Santos *et al.*, 2006). It consists of a series of pools, arranged in a stepped pattern, separated by cross-walls that can be equipped with submerged orifices at the bottom and surface notches. Hydraulic characteristics in pool-type fishways vary according to the pool dimensions, configuration and dimensions of orifices and notches, slope and discharge. A number of studies have addressed the flow circulation patterns, the jet characteristics and the turbulence generated by the energy dissipation in pools for different configurations, and their relevance for the development of suitable hydraulic criteria for passage of salmonid species (Rajaratnam and Katopodis, 1986; Rajaratnam *et al.,* 1992; Wu *et al.*, 1999; Ead *et al.*, 2004; Puertas *et al.*, 2004; Liu *et al.*, 2006; Barton *et al.* 2008). However, passage studies focused on coarse species are scarce and therefore highly desirable (Stuart and Mallen-Cooper, 1999; Katopodis, 2005). This requirement is highlighted in Iberian rivers where cyprinid fishes are frequently the most abundant group of species encountered (Doadrio, 2001).

The Iberian barbel *Luciobarbus bocagei* (Steindachner, 1864) is one of the most common cyprinid species in Iberian rivers, though its migration ecology has been assessed only in recent studies (Santos *et al.*, 2005). However, little is known about this specie’s response to specific hydraulic characteristics, such as water velocity and turbulence. These two hydraulic variables are considered to play an essential role in successful fish passage through a fishway (Rajaratnam *et al.*, 1998). Turbulent kinetic energy (K) and Reynolds shear stress, are two interdependent turbulence descriptors that naturally affect fish migration, but for which, detailed knowledge on their effects on fish movements is scarce (Rajaratnam *et al.*, 1988; Odeh *et al.*, 2002). Due to the fact that both turbulence kinetic energy and Reynolds shear stress are important indicators of turbulence effect on a fish's body, it's clear there is a need to understand how Iberian barbel sense, react and use these hydraulic phenomena in their movements within fishways, in order to develop robust guidelines that are useful for future fishway designs. However, their assessment under natural conditions is extremely difficult and possibly inaccurate due to the plethora of interacting factors. To be successful, studies should be based on balanced experimental designs, in which the variables of interest can be manipulated. Studies conducted on such conditions offer an excellent opportunity to gain generic insights into fish behaviour (Kemp *et al.*, 2006).

The main goal of this study is to understand the effects of water velocity and turbulence, expressed as turbulent kinetic energy (K) and Reynolds shear stress, on the upstream movements of Iberian barbel under experimental conditions in a full scale pool-type fishway. Specifically, the following questions should be answered: (a) how do the different hydraulic parameters relate to the transit time of distinct fish size-classes within the fishway, i.e., are smaller size-classes more affected by hydraulics than larger conspecifics? and (b) which hydraulic parameters affect fish performance within the fishway the most?

3.2. MATERIALS AND METHODS

Experimental fishway

The study was conducted in an indoor full scale pool-type fishway installed at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon. The structure was 10 m long, 1 m wide and 1.2 m high, externally reinforced by fiberglass sidewalls (Figure 3.1). It consisted of six pools (1.9 m long x 1.0 m wide x 1.2 m high) divided by five PVC cross-walls, each equipped with a submerged orifice and a surface notch of adjustable area. Two consecutive orifices were positioned on opposite sides of the cross-walls, creating a sinusoidal flow path. The fishway was set at a slope of 8.5%, which is within the range of slopes commonly used in this type of hydraulic devices (Larinier, 2002). A concrete tank (1.50 x 1.00 x 1.20 m) located at the upstream end of the flume, provided a smooth flow entering in the flume. The fishway also encompassed an acclimation chamber (4.0 x 3.0 x 4.0 m) at the downstream end of the channel, which was separated from the main structure by two mesh panels. Water used in the experiments was drawn from domestic water supply (soft water) and was recirculated through the laboratory pumping system (maximum capacity of 259 $l.s^{-1}$) for at least two weeks prior to the experiments to ensure dechlorination and "maturation" throughout (Copp *et al.*, 1998), and checked for temperature, hardness, pH and dissolved oxygen at the beginning and at the end of experiments by means of a multiparametric probe (Hydrolab, Quanta model).

Fishway discharge was measured by a magnetic flow meter located in the supply pipe and controlled by a slot valve at the upstream tank. Water surface levels were measured using graduated scales placed on the side-wall of the pool, in the vicinity of the cross-walls and middle point of the pool. The water level within the structure was regulated by a slot gate at the downstream end of the facility.

Hydraulics

By varying fishway discharges (Q) between 38.5 $l.s^{-1}$ and 77.0 $l.s^{-1}$, and the area of submerged orifices (A_o) between 0.03 m^2 and 0.06 m^2, four experimental conditions were tested (Table 3.1). Because Silva *et al.* (2009) found that Iberian barbel avoided notched surface openings, the surface notches, under all experiments, remained closed.

Detailed instantaneous velocity measurements were conducted using an instantaneous 3D Acoustic Doppler Velocimeter (ADV) oriented vertically down (Nortek AS). The advantage of using this device relies on its ability to adequately measure the three-dimensional velocity components (x, y, z) of flowing water (Papanicolaou and Maxwell, 2000; Odeh at al., 2002; Ead *et al.*, 2004; Guiny *et al.*, 2003). Velocity measurements were recorded at 25 Hz for a sampling period of 90 s in each point on the grid. Preliminary tests were conducted to define the ADV sampling period needed for an accurate determination of the mean velocity, turbulent kinetic energy and Reynolds shear stress. Tested sampling periods ranged from 5s to 350s. It was found that velocity became almost constant for sampling periods greater than 30s, therefore a sampling time of 90s was considered to be representative for an appropriate determination of mean velocity and turbulence within the pool. Because the flow pattern and the head drop between the pools were found to be the same in all pools (Δh=0.16m), measurements were made in the second downstream pool. Measurements were taken at different horizontal planes parallel to the flume bottom, namely at 25%, 50% and 80% of the pool mean depth (h_m). A predefined grid of 48 measurement points distributed according to the velocity fluctuations expected was used as a reference to the measurements in each plane. Altogether, 2500 instantaneous measurements were recorded for each sampling point.

To understand the velocity fields at the different planes – horizontal (XY), vertical (XZ) and transversal (YZ) - within the pools, the ratios between the maximum velocity in each plane (Vxy_m, Vxz_m and Vyz_m) and the maximum flow velocity at the orifice (V_o) were calculated for the four experiments.

Turbulence descriptors - turbulent kinetic energy and Reynolds shear stress - were calculated based in the instantaneous velocities registered. The local velocity in a turbulent region can be decomposed of a temporal mean value plus a component that represents thevelocity fluctuation about the mean. Accordingly:

$$V(t) = \overline{V} + V'(t) \qquad (3.1)$$

where $\overline{V}$ is the mean velocity at the point during the sampling period and $V'(t)$ is the fluctuating component of velocity at sampling time t. Turbulent kinetic energy (K) is defined as:

$$K = \frac{1}{2}\left(u'^{2}_{rms} + v'^{2}_{rms} + w'^{2}_{rms}\right) \qquad (3.2)$$

where u', v' and w' are the longitudinal, transversal, and vertical fluctuating velocities, respectively. This parameter represents the kinetic energy of the velocity fluctuations, i.e. greater fluctuation from the mean flow represents greater turbulent kinetic energy. The size of the turbulent fluctuations is therefore important to consider when studying upstream movements of fish species. Small-scale turbulence associated with tiny eddies may cause localized damage on fish body surfaces (bruises, scale loss), whereas larger-scale turbulence, i.e. greater than fish size, can cause spin, fish disorientation and loss of equilibrium which ultimately affect their upstream movement (Odeh *et al.*, 2002). To enable comparisons with others studies, K was formulated in dimensionless terms (normalized) using the maximum velocity in the orifice (V_o), according to the following equation:

$$\kappa = K^{0.5} / V_o \qquad (3.3)$$

The Reynolds shear stress represents another fluid force that involves a velocity gradient, and therefore is of major importance for fish passage studies. This parameter represents a force per unit area and occurs when two water masses or layers of different velocities are parallel or adjacent to each other. Fish may therefore experience shear stress when moving between two water masses of different velocities or when moving near a solid structure (Cada *et al.*, 1999).

To better understand which forces are primarily acting on the body surface of fish and therefore influencing their upstream movements, this parameter was partitioned on three components according to the forces present on each plane: longitudinal (forces acting on the XY plane), vertical (forces acting on the XZ plane) and transversal (forces acting on the YZ plane). For the horizontal component, shear stress is defined by:

$$-\rho \overline{u'v'} \qquad (3.4)$$

, where ρ is the water density, u' and v' are the fluctuating velocities in the X and Y directions, respectively. The variations of the Reynolds shear stress in each of the three dimensions were therefore assessed at two different layers from the flume bottom: at $0.25h_m$ (close to the bottom) and at $0.80h_m$ (near the surface). To allow for comparisons, this parameter was also made dimensionless according to the maximum velocity in the orifice (V_o) according to the following equation, for the horizontal plane (XY) :

$$\overline{(-u'v')_m} / V_o^2 \qquad (3.5)$$

where the subscript *m* refers the maximum value in a transverse profile. The variations of the dimensionless Reynolds shear stress at the vertical $\overline{(-u'w')_m} / V_o^2$ and at the transversal plane $\overline{(-v'w')_m} / V_o^2$ were also calculated to $z=0.25h_m$ and $z= 0.80h_m$.

Fish

Iberian barbels were captured at the River Sorraia, the largest tributary of the River Tagus (central Portugal). Further details of the sampling area are included in Collares-Pereira *et al.* (1995). Sampling was undertaken using electrofishing (Electrocatch International, Sarel model WFC7_HV, Wolverhampton, UK) with low voltage (250 v) and with a 30 cm diameter anode. Fish were captured during the natural reproductive migration season, which generally takes place from April to June (Santos *et al.*, 2005). Only mature individuals, as shown by *in situ* macroscopic observations of fish gonads development stage, particularly their volume, vascular irrigation and visibility of oocytes, and the presence of nuptial tubercles (Agostinho *et al.*, 2007) were selected for the study. Fish (N=80) were brought to the laboratory, and measured for total length (TL). To test for size-related differences in species behaviour, fish were separated into two size-classes according to reported differences in age and growth

(Lobón-Cerviá, 1982; Lobón-Cerviá & Fernandez-Delgado, 1984), although such divisions are somewhat arbitrary and flexible depending on catchment characteristics (Oliveira *et al.*, 2002): small (15 < total length (TL) < 25 cm) and large adults (25 ≤ TL < 35 cm). Iberian barbel of each size-class (n = 40; 20 individuals per tank) were then placed in four tanks (length x width x height = 1.45 x 0.70 x 0.80 m) equipped with ELITE aerator systems and mechanical filters. To recover from transport and handling stress, fish were kept in the tanks for at least one week before experiments started. During that period, fish were fed daily with pond sticks (Tetra Pond), until 24 h prior to experimentation. The difference in water temperature between the tanks and the fishway (mean temperature = 18ºC) was less than 2ºC.

Fish experiments took place between the 10th and 18th of May 2007 from 17h00 to 22h30, to encourage attempts by this species which typically migrates at dusk (Santos *et al.*, 2005). Each experiment lasted 1.5 hours and was conducted by using one adult fish of each size-class simultaneously. Individuals were first introduced in the acclimation chamber where they remained for 12 hours prior to experimentation and were prevented from entering the flume by two mesh panels. Once the discharge in the flume was brought to the desired level, the mesh panels were removed and fish were allowed to ascend the fishway of their own volition. Fish experiments were conducted under the four previously tested hydraulic conditions with 10 replicates each, giving a total of 40 trials. Fish behaviour was continuously monitored through the glass sidewalls of the fishway by means of direct observation and a video recording system. Direct observations were performed during the entire time of an experiment and were made at approximately 1 m distance from the channel, approaching and leaving discreetly the observation points, respectively before and after each experiment. This caused no disturbance to the fish, as revealed by a previous pilot study (unpublished data). Each operator followed a single fish, registering all of its movements, including the time taken by the fish i) to enter the flume, ii) to ascend from one pool to the next and iii) to successfully negotiate the fishway. Observations were also supplemented by three digital video cameras focused on the second pool, which was considered to be representative of the remaining hydraulic conditions (see Hydraulics). Two of the cameras were positioned at a distance of 2 m from both side-walls of the pool, whereas the other was placed 3 m above the water surface. In addition, a 1.90 x 1.00 m reference grid containing 15 contiguous sequentially numbered cells (each 0.38 x 0.33 m) was created and placed above this pool to aid in the video monitoring process (Figure 3.1).

Video records were analyzed by a single operator, using the IVision Labview software from National Instruments (http://www.ni.com), allowing the collection of continuous exact locations of fish within the pool. An individual fish was considered to occupy one cell, when more than half of its body length was within a cell's boundaries. The time spent by a fish in each cell of the grid (transit time) was determined and related to the hydraulic parameters values previously found.

Statistical analyses

Kruskal-Wallis ANOVA was employed to test the hypothesis that, for each fish size-class, the transit times in each cell of the grid were equivalent among experiments. Correlations between transit time and mean velocity, turbulent kinetic energy and three-dimensional Reynolds shear stresses were analysed using the Spearman rank coefficient. Data were pooled over the four experimental conditions, as a previous analysis revealed water velocity vectors to be spatially similar among experiments, though increasing proportionally in terms of magnitude with increasing flow discharge. Analyses were performed using data collected at $z = 0.25h_m$ instead of considering mean values obtained from all three planes, as visual observations and video monitoring showed that fish movements were found to occur preferentially close to the bottom of the fishway.

3.3. RESULTS

Hydraulics

The mean velocity patterns for the three horizontal planes at $0.25h_m$, $0.50h_m$ and $0.80h_m$ above the bottom of the flume for $Q = 47.5$ L.s^{-1} are shown in Figure 3.2 . In the horizontal plane at 0.25 h_m,, closest from the flume bed, two different regions could be clearly distinguished: the jet region, with maximum velocities occurring at a distance of 0.40 m downstream from the cross-wall and reaching 0.83 m.s^{-1}, and a large recirculation region, extending from the jet zone to the opposite side-wall, characterized by low velocities and reversed flow directions. At the plane closest to the water surface (0.80 h_m), a uniform recirculation region could be observed, with moderate to high velocities (0.50-0.77 m.s^{-1}), occurring along this plane, particularly in the vicinity of the downstream cross-wall. The ratio between the maximum velocity in each plane (Vxy_m, Vxz_m and Vyz_m) and the maximum velocity in the orifice (V_o) are shown in Figure 3.3. It can be seen that in the horizontal plane (XY), maximum velocities occur near the bottom of the flume increasing with flow discharge (Figure 3.3a). In both vertical (XZ) and transversal (YZ) planes, the occurrence of higher velocities with increasing discharge was less evident. Nonetheless, patterns of velocity distribution could still be observed along the pool, particularly at higher discharges: on a vertical plane, maximum velocities were found to be greater in the vicinity of the side-wall adjacent to the orifice and decreasing towards the opposite side-wall (Figure 3.3b). Similarly on a transverse plane, the maximum velocities varied slightly with the increasing discharge peaking in the vicinity of both cross-walls (0.40 V_o), ranging between 0.20-0.30 V_o in the remaining areas (Figure 3.3c). The contours of the dimensionless turbulent kinetic energy ($Q = 47.5\ l.s^{-1}$) at $z=0.25h_{m}$, and $z=0.80h_m$ are shown in Figure 3.4. Turbulence was found to be higher near the bottom of the flume ($z = 0.25h_m$), particularly along the streamline between the submerged orifices. At the level closest to the surface ($z = 0.80h_m$), a rapid decay was observed within the same jet region. In contrast, in the recirculation area, turbulence remained low (around 0.08-0.10 V_o) at both levels, though a small increase was noted near the surface.

The variations of Reynolds shear stress in all three planes are shown on Figure 3.5. The absolute value of this parameter was found to decrease in both the horizontal and vertical planes when moving from the bottom ($z = 0.25h_m$) to the surface ($z = 0.80h_m$). Accordingly, at $z = 0.25h_m$, the values of absolute horizontal (Figure 3.5a) and vertical shear stress (Figure 3.5c) were greater in the vicinity of the upstream cross-wall (flow inlet), decreasing from the middle part of the pool towards the downstream end, with these patterns being clearer at higher discharges. At the level near the surface ($z = 0.80h_m$), absolute shear forces remained almost constant along the pool length and among experiments, ranging from 0 to 0.01 (Figure 3.5b and Figure 3.5d, respectively). Variations in transverse Reynolds shear stress at $z = 0.25\ h_m$ (Figure 3.5e) and $z = 0.80\ h_m$ (Figure 3.5f) were quite low, remaining almost constant along the pool length and throughout experiments.

Fish

In all the experiments, fish exhibited a high capacity to negotiate the fishway, though some size-related differences were noted (Figure 3.6a). Accordingly, larger adults presented a higher rate of success (mean = 79%) in ascending the fishway, relative to small adults (mean = 59%). Similarly, larger adults took less time (mean ± SD (min): 5.7 ± 1.3) to ascend the fishway, when compared to small-size individuals (mean ± SD (min): 8.0 ± 0.4) (Figure 3.6b).

Transit time did not differ among experiments (Kruskal-Wallis ANOVA: $p>0.05$) and was found to be lower with increasing mean velocity for both size-classes, particularly for small adults (Spearman rank correlation: small adults: $r=-0.30$, $p<0.05$; large adults: $r=-0.27$,

$p < 0.05$). The relationship between mean values of velocity within each cell (see Figure 3.1b for a general scheme) and the respective fish transit time at $z=0.25h_m$ is shown on Figure 3.7. Both size-classes used cells with low velocity values (0.20 - 0.40 $m.s^{-1}$).

The plot of fish transit time with turbulent kinetic energy (K) is shown on Figure 3.8 for the different cells within the pool. It shows that small (Figure 3.8a) and large adults (Figure 3.8b) used mainly areas with low K (< 0.05 $m^2.s^{-2}$). Therefore, a significant negative correlation between K and fish transit time was found for both fish sizes (Spearman rank correlation: small adults: $r=-0.39$, $p<0.01$; large adults: $r=-0.35$, $p< 0.01$).

Finally, the relation between Reynolds shear stress components (horizontal, vertical and transversal) and fish transit time in each cell is shown on Figure 3.9. Correlations between the former and the components of Reynolds shear stress in the different planes yielded different results. Accordingly, a negative association between fish transit time and the horizontal shear stress was found for both size-classes, particularly for small adults (Figure 3.9a and Figure 3.9b) (Spearman rank correlation: small adults: $r=-0.45$, $p<0.001$; large adults: $r=-0.36$, $p< 0.01$). Overall, individuals spent less time in cells with higher shear stress values (absolute values ranged from 20 to 60 $N.m^{-2}$) on this plane. This correlation was the strongest among all tested hydraulic characteristics against transit time, thereby indicating that the horizontal component of Reynolds shear stress may stand as the hydraulic parameter affecting fish behaviour within the fishway the most. In contrast, no significant relations were found for the vertical (small adults: $r =-0.22$; $p>0.05$; large adults: $r = -0.19$; $p>0.05$) (Figure 3.9c and Figure 3.9d) and transverse (small adults: $r = -0.21$; $p>0.05$; large adults: $r = -0.18$; $p>0.05$) (Figure 3.9e and Figure 3.9f) components, i.e. regardless of transit time, fish remained in cells with low absolute values of non-horizontal shear stress (*c,* 10 $N.m^{-2}$).

3.4. DISCUSSION

This study quantified the effects of water velocity and turbulence flow descriptors turbulent kinetic energy and Reynolds shear stress, on the upstream movements of a potamodromous fish, the Iberian barbel, within an experimental pool-type fishway. In testing the response of fish to distinct hydraulic conditions in an experimental fishway, an appropriate physiological condition is required for fish to be motivated to swim upstream without being forced through. In addition, to avoid biased conclusions, experimentation should also be performed during periods and under conditions that are relevant to the animals in their native habitat (Castro-Santos, 2004). In the present study, the high proportion of fish that negotiated the fishway in response to every fishway discharge strongly indicates that these factors were present. Furthermore, continuous observation on fish movements did not indicate any unnatural behaviour caused by operational procedures. Gas supersaturation due to pumping water was unlikely to occur, as typical related symptoms, such as heavy gasping or bubbles / blisters around the head and eyes of fishes were not found throughout the experiments (Bouck, 1980). Similarly, gasping or presence of darkened gills, symptoms of an excess carbon dioxide on the water, was not registered at all during the study.

The configuration of the fishway used in the present study – surface notches closed and presence of orifices of adjustable area (0.03-0.06 m^2) located on opposite sides of the cross-walls - was adequate as shown by an overall high percentage of passing fish, though this was more evident in the case of large adults (*c.* 80%). Water velocities were found to be the highest (*c.* 0.80 $m.s^{-1}$), close to the flume bed, namely in the jet region, but they were within the range of critical swimming speed for this species (Mateus *et al.*, 2008). In addition, the volumetric power dissipation, which provides an indication of average pool turbulence, was always < 150 $W.m^{-3}$; this is considered as the upper limit for fishways used by cyprinid species (Larinier, 2008). Despite their weaker swimming capability relative to larger individuals, small adult barbel also managed to successfully ascend the fishway, though to a lesser extent (*c.* 60%). Although the concept of fishway efficiency (defined as the proportion of fish present at the acclimation chamber that successfully negotiated the fishway) has not been formally defined in terms of minimum standards (Larinier, 1998), it is generally considered that efficiencies should be 90-100% for diadromous species, whereas for potamodromous cyprinid species, such as the Iberian barbel, the successful passage of a certain number of individuals, in relation to the population in place may be sufficient to ensure the longitudinal connectivity of river systems and avoid fragmentation of the populations. It is therefore believed that the configuration of the fishway was well designed, as shown by a fairly “reasonable” proportion, i.e. 60-80%, of Iberian barbel that successfully negotiated the device.

Iberian barbel spent higher transit times in cells with low water velocity (0.20-0.40 $m.s^{-1}$) but this effect was more prominent on the smaller size-class, as shown by a higher negative correlation coefficient between this parameter and fish transit time for the four experiments. These conditions were mainly found close to the bottom of the fishway ($z = 0.25h_m$) on the recirculation region, extending from the jet zone to the opposite side-wall. Several studies have shown that recirculation regions on pool-type fishways can become traps for fish, by drastically increasing the transit times in each pool and thus compromising the clearing of the fish pass (Tarrade *et al.*, 2008). Although the notion that this phenomenon might have affected some of the fish is not excluded, particularly the smaller individuals, it is believed that most fish clearly used these areas for resting before a subsequent upstream movement through the higher-velocity areas within and in the vicinity of the orifice. This is also supported by the high proportions of fish that even at lower discharges successfully negotiated the fishway.

As with velocity, Iberian barbel were mainly found to occupy areas with low turbulent kinetic energy (K), with small adults displaying a higher effect concerning the time spent on each cell, relatively to large adults. These areas could be found close to the bottom of the fishway ($z = 0.25h_m$) and corresponded to the previous recirculation region, contiguous with the jet zone. The occurrence of barbel, a species with limited swimming ability (Doadrio, 2001), spending higher transit times in low velocity and kinetic energy cells would naturally be expected, since energy expenditures to maintain fish position are typically lower in such areas (Pavlov *et al.*, 2000). In a study designed to monitor the physiological swimming effort of Iberian barbel, Mateus (2007), using individuals tagged with coded electromyogram radio transmitters, also found this species to rest in positions close to the bottom at a mean velocity of 0.30 $m.s^{-1}$. The use of low turbulent kinetic energy locations by Iberian barbel as resting areas before subsequent efforts to traverse areas of higher velocity and turbulence (i.e. near or through orifices), highlights the importance of this parameter, that should be taken into account when designing fishways for this species.

The effects of Reynolds shear stress on the movements of Iberian barbel through the fishway were found to differ according to the component considered in each of the three dimensions. Accordingly, the correlations between fish transit time and the horizontal Reynolds shear stress were the highest among all tested hydraulic variables, suggesting the importance of this variable as a key-parameter determining Iberian barbel' movements within pool-type fishways. Reynolds shear stress is negligible in sections where water velocity is fairly uniform. However, when water velocity changes on scales similar to the size of a fish, shear stress can occur, causing fish disorientation and localized injury. In the present study, water velocity was found to vary across different horizontal planes, increasing from the surface to the bottom. The result of these changing velocities, detected by the fish through the superficial neuromasts of the lateral line (Montgomery *et al.*, 1997), might have acted upon the components of the force that are parallel to the fish surface area, therefore creating a higher shear stress on the body of the fish. As with the other hydraulic parameters, the effects of Reynolds shear stress were most prominent in the smaller-size individuals, as shown by the highest correlations with fish transit time, highlighting the use of different size-classes upon studying the effects of hydraulics on fish.

Though fish have developed numerous adaptations to the levels of shear stresses occurring in natural environments (≤ 30 $N.m^{-2}$ in small to medium sized streams), high and potentially undesirable values can occur where rapidly flowing water passes within confined man-made structures such as submerged orifices of pool-type fishways (Cada *et al.*, 2006). This is in accordance with the findings of the present study, where turbulence was maximal in the vicinity and within submerged orifices. On the horizontal plane, barbel occupied positions with absolute Reynolds shear stresses up to 60 $N.m^{-2}$ during higher discharges. This value, though larger than those generally observed under natural conditions, may not be sufficient to cause injuries or mortalities, which typically occur at much higher levels (≥ 700 $N.m^{-2}$) (Cada *et al.*, 1999). Nevertheless, the prospect that the higher shear stresses reported on this plane may have caused some minor disorientation and reduction of swimming performance at higher discharges is not excluded, particularly for some of the smaller individuals, as shown by a lower percentage of successful passage compared to larger fish. Such disorientation may have been caused by a more pronounced effect of large turbulence vortex systems on their smaller body surface, compared to larger individuals. It is known that flowing water has a complex vortex structure, a torque of hydrodynamic rotating forces increasing from the center to the periphery, with various vortex formations of different sizes (Odeh *et al.,* 2002). The sizes of these vortexes are of great importance for the balance of fish in a turbulent flow, i.e., if a vortex is much smaller than a fish, its balance should not be affected due to an even distribution of the moments of force along its body. In contrast, if vortex and fish sizes are similar, the hydrodynamic rotating forces introduce a torque which tends to overturn the fish and decrease stability (see Lupandin (2005) for a schematic view). In other words, the larger an individual is, the larger the vortex required to affect its balance. The presence of larger vortex systems is typically more pronounced in higher turbulent areas (Lupandin, 2005). In the present study, such areas could be mainly found near the bottom of the flume along the streamline between the submerged orifices. Though not quantified, the expected higher proportion of larger vortices in this region could have therefore affected balance and hence, the swimming performance of smaller size individuals. This was particularly evident in the vicinity of the orifices at higher discharges, when some of these fish were seen to spread their pectoral fins in an attempt to stabilize their body position. Such behaviour increases the hydraulic resistance of their body and consequently decreases their swimming performance. The modification of internal flow characteristics in the pools by placement of submerged structures to examine the extent to which turbulence, particularly the horizontal Reynolds shear stress component can be reduced, and thus facilitate passage of small individuals, should be considered on future fish passage studies. Their inclusion in numerical flow simulations in association with fish activity monitoring techniques, such as electromyogram telemetry, would surely contribute to advance the knowledge of species behavioural patterns during obstacle negotiation with different hydraulic conditions.

3.5. CONCLUSION

The configuration of the fishway was well designed, given the "considerable" proportion of Iberian barbel that successfully negotiated the structure. However, size-related differences were found: overall, larger adults negotiated the fishway in a greater proportion and took less time to ascend, relatively to small ones. Of the tested hydraulic characteristics, the horizontal component of Reynolds shear stress was found to be the hydraulic parameter that most strongly affected movements of the species, in particular of the smaller-size individuals, which seemed to avoid areas of high turbulence. A possible cause for their lower rate of passage success could be the impact of the higher turbulence (and consequently larger turbulence vortices) observed in the vicinity of the submerged orifices, on fish body surfaces. Future work should consider ways of increasing the success of passing small barbel and other benthic species through the pool-type fishway, by minimising any possible disorientation and shortening the time spent by such individuals in the pools. An alternative approach could involve the introduction of artificial rough substrates on the bottom of the flume in an attempt to attenuate the higher shear stress zones close to the submerged orifices, through the smoothing of the horizontal velocity gradients. Finding ways of reducing the size of the recirculation region by the placement of structural elements in the pools could be another possible solution which should also be considered. In every case, attention should be given on characterizing the water velocity and shear stress in the vicinity of these structures, providing detailed descriptions of the behaviours of fish traversing such areas and identifying conditions that act to increase or decrease the number of successful fish passage attempts.

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Table 3.1. Details of experimental conditions: submerged orifices area (A_o), head drop between pools (Δh), volumetric power dissipation (P_v), pool mean water depth at 25, 50 and 80%. Fish size of individuals used in the experiments are also shown.

Experiments	Variables											
	A_o (m^2)	Δh (m)	Q ($l.s^{-1}$)	P_v ($W.m^{-3}$)	h_m (m)	25% h_m (m)	50% h_m (m)	80% h_m (m)	Small adults: 15< TL <25cm		Large adults: 25≤ TL <35cm	
									N	Mean ± SD (cm)	N	Mean ± SD (cm)
E1	0.03	0.16	38.5	37.0	0.79	0.20	0.40	0.63	10	19.07 ± 1.76	10	28.87 ± 2.59
E2	0.04	0.16	47.5	47.8	0.86	0.21	0.43	0.68	10	19.85 ± 2.49	10	28.44 ± 3.11
E3	0.05	0.16	62.7	63.1	0.85	0.21	0.42	0.68	10	19.74 ± 2.14	10	28.67 ± 2.89
E4	0.06	0.16	77.0	78.4	0.84	0.21	0.42	0.67	10	19.65± 2.41	10	28.25 ± 3.07

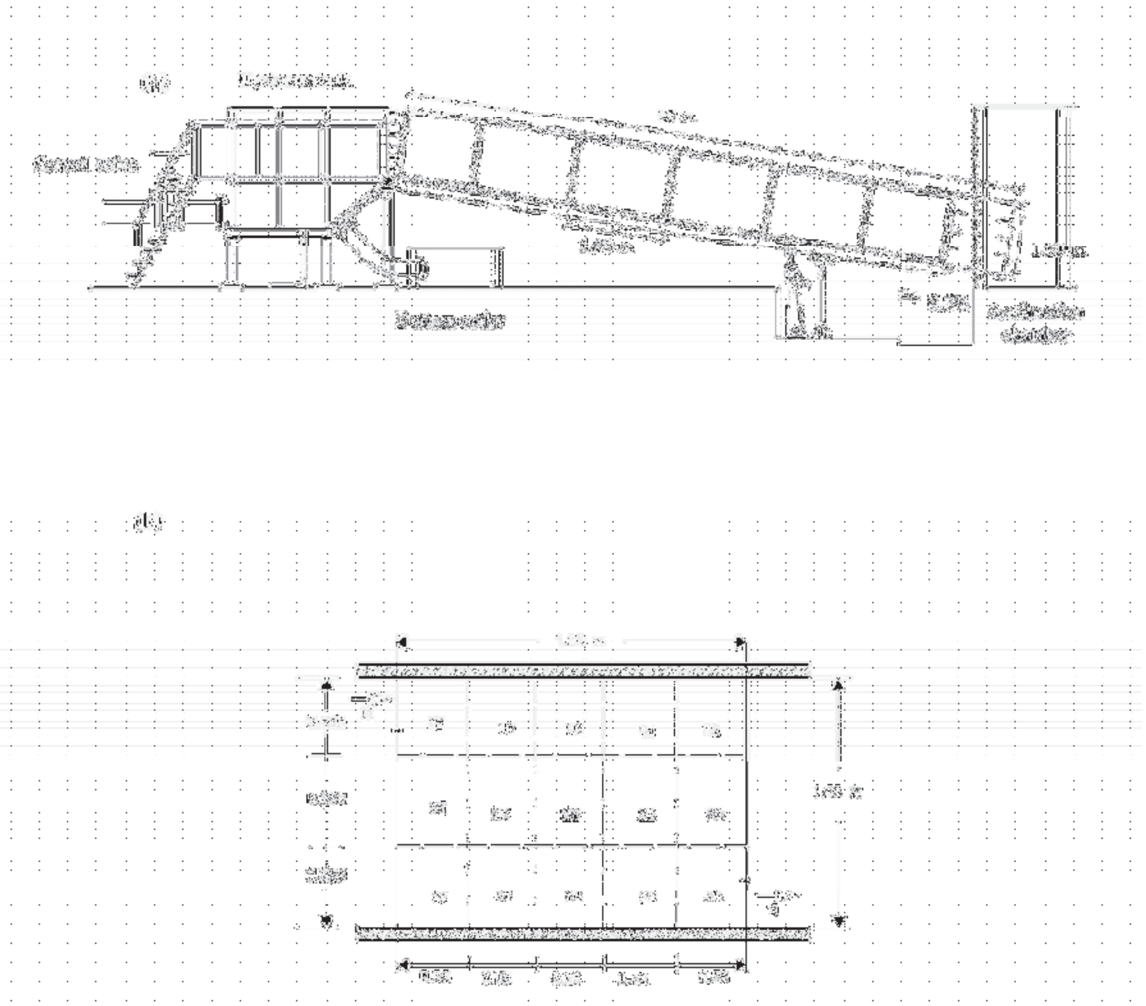

Fig. 3.1. (a) Side view of the experimental full scale pool-type fishway at the National Laboratory for Civil Engineering; (b) reference grid used for fish behaviour observation.

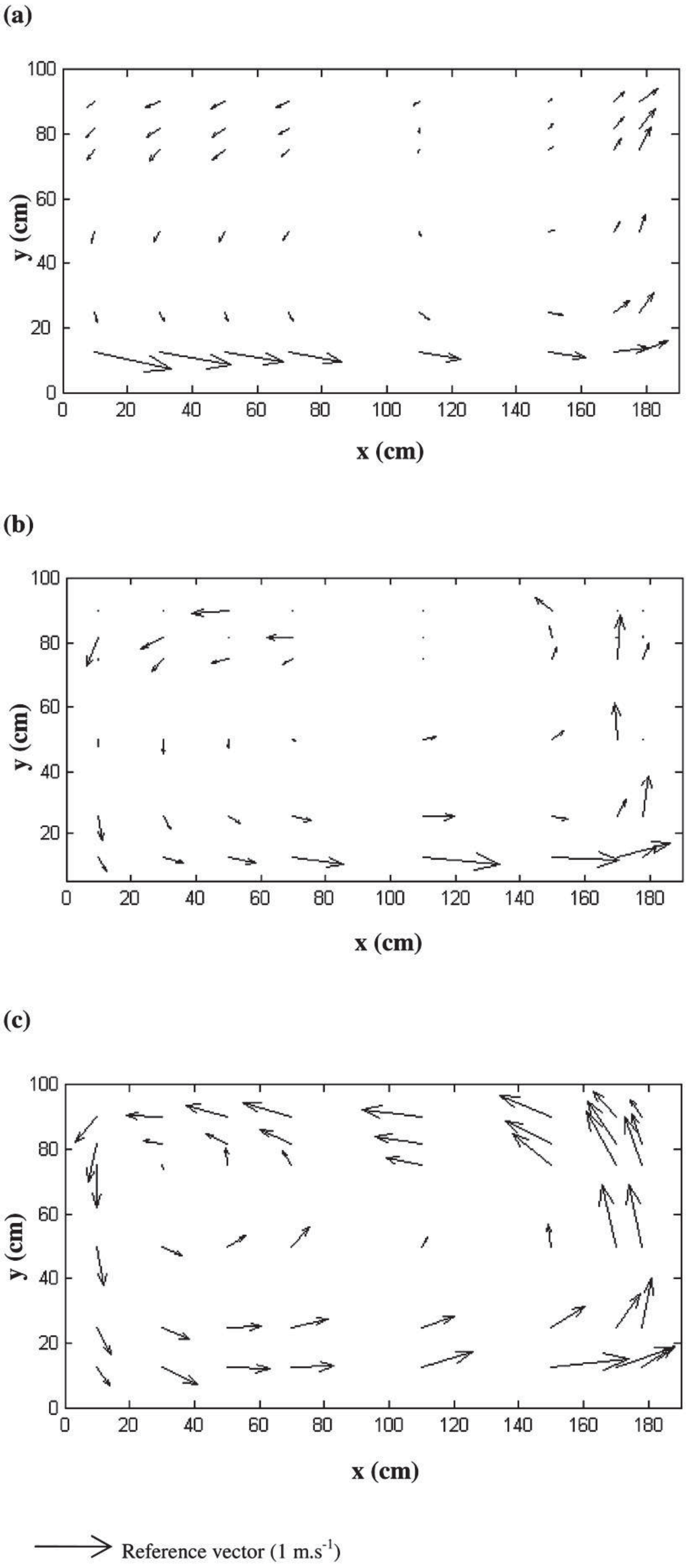

Fig. 3.2. Plane velocity field in the pools for Q = 47.5 l.s^{-1}: (a) z = 0.25h$_m$; (b) z = 0.50h$_m$; (c) z = 0.80h$_m$. Flow from the orifice enters at the bottom left of the diagram.

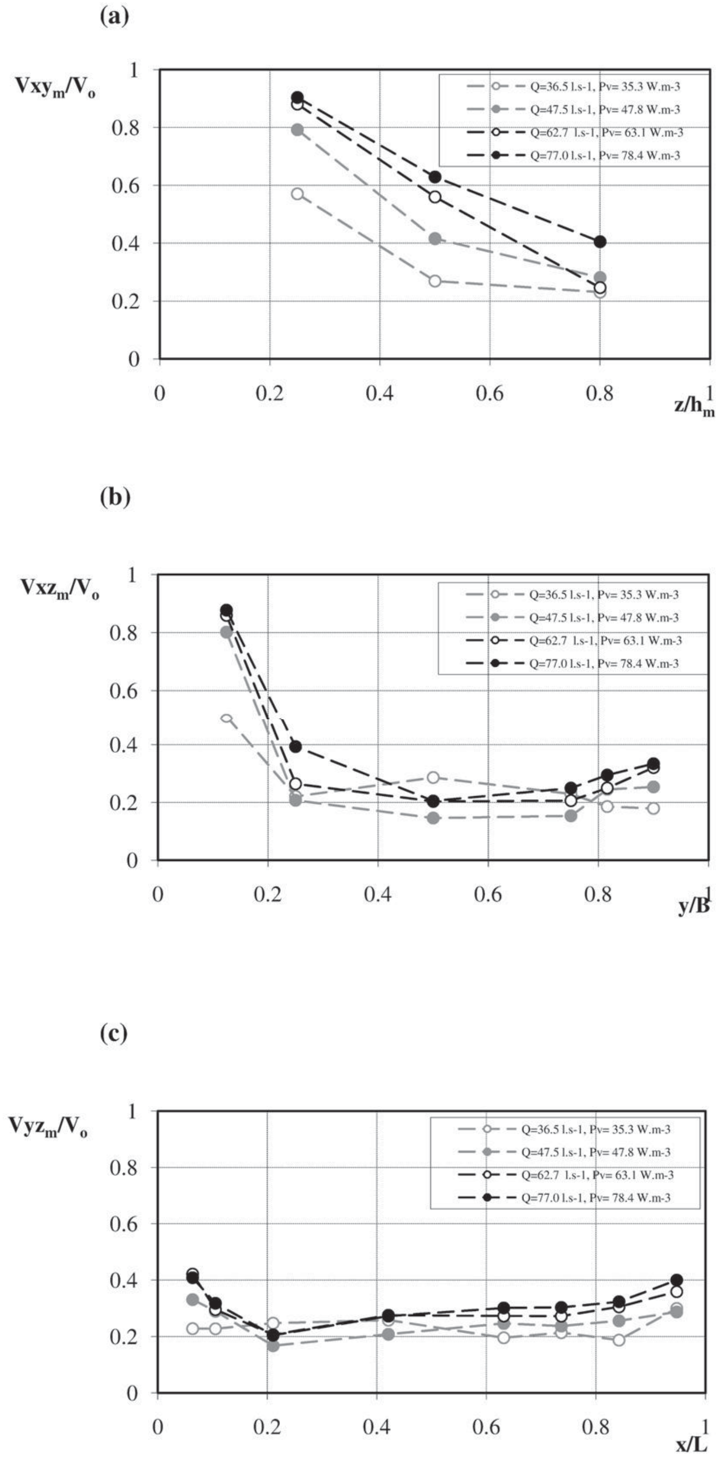

Fig. 3.3. Dimensionless maximum velocities at various tested discharges on different planes: (a) horizontal plane (XY); (b) longitudinal plane (XZ); (c) transverse or cross section plane (YZ).

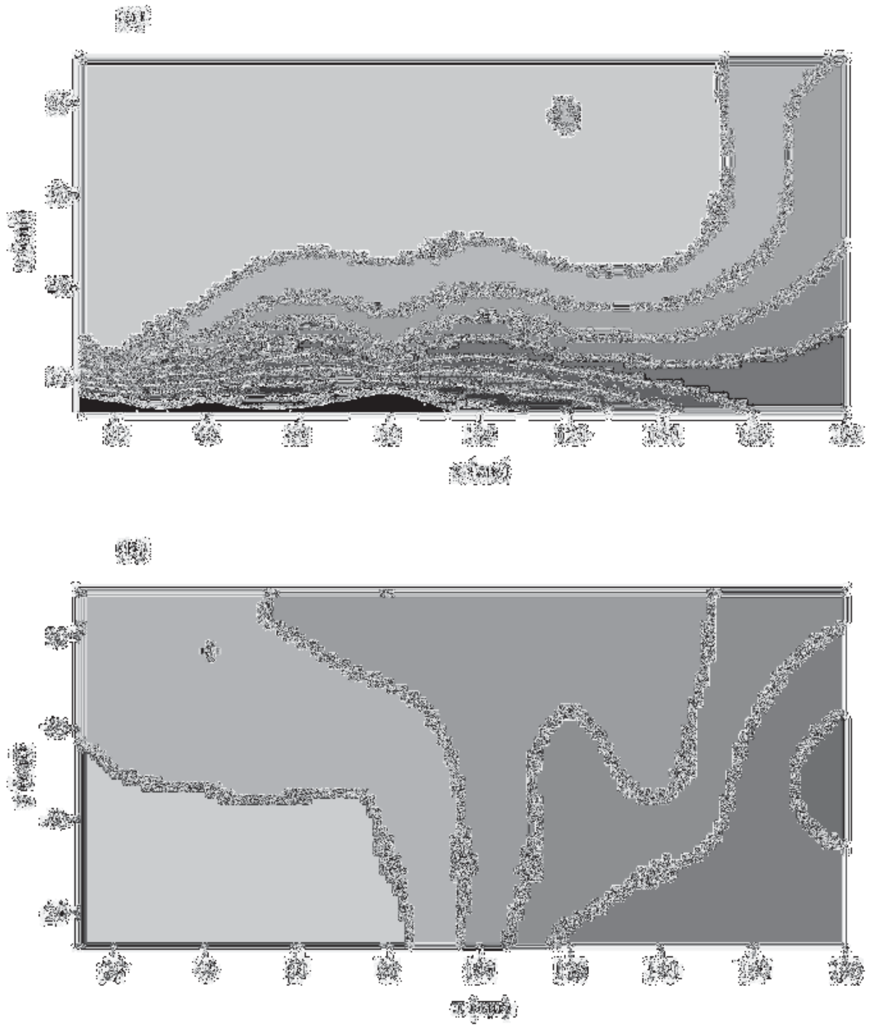

Fig. 3.4. Contours of dimensionless turbulent kinetic energy $\kappa = K^{0.5}/V_s$, for Q = 47.5 l.s^{-1} at different horizontal planes: (a) z = 0.25 h_m; (b) z = 0.80 h_m. Flow from the orifice enters at the bottom left of the diagram.

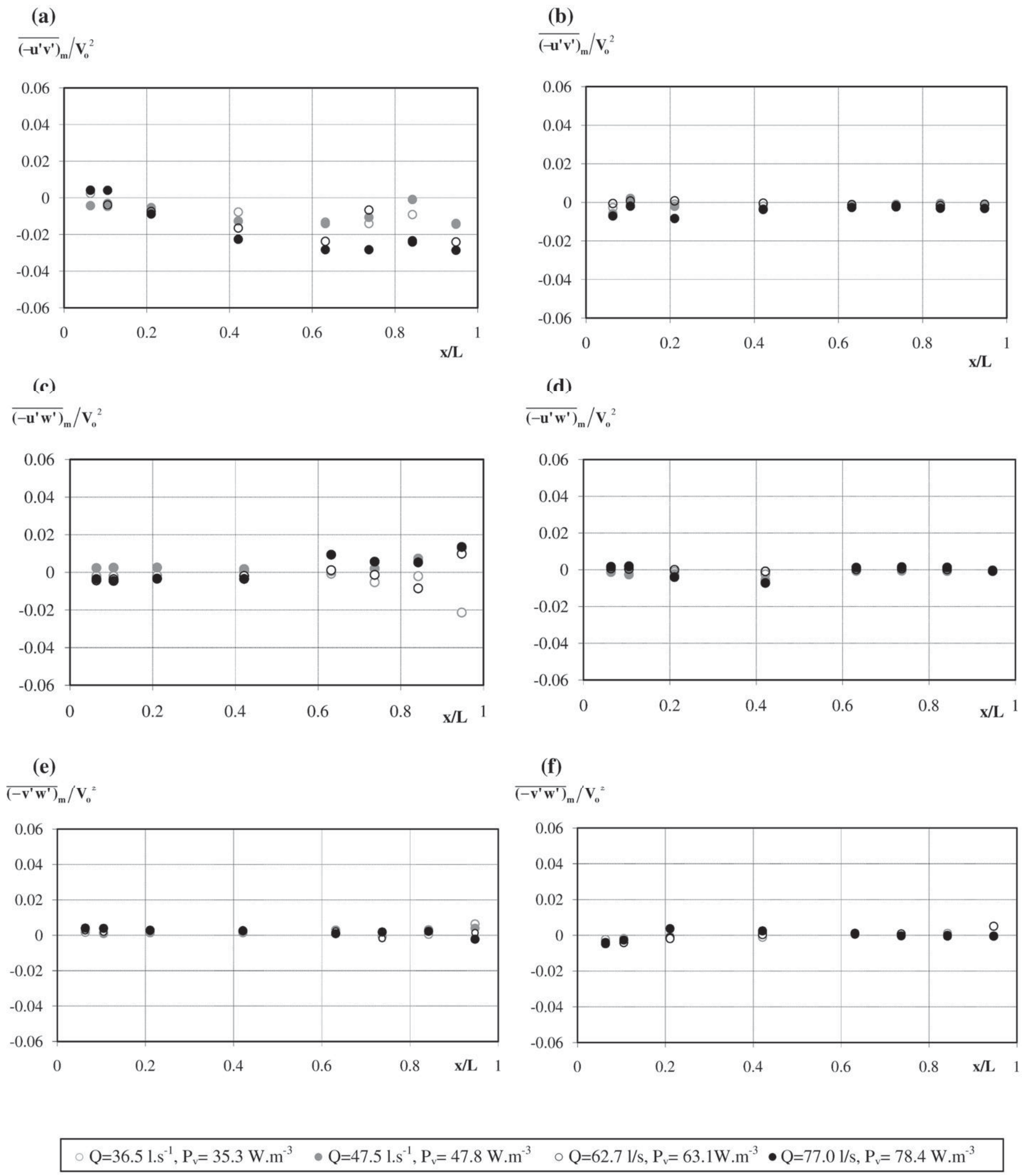

Fig. 3.5. Variation of dimensionless Reynolds shear stress at various tested discharges on different planes: (a) XY-plane at $z = 0.25h_m$ (b) XY-plane at $z = 0.80h_m$ (c) XZ- plane at $z = 0.25h_m$ (d) XZ- plane at $z = 0.80h_m$ (e) YZ- plane at $z = 0.25h_m$ (f) YZ- plane at $z = 0.80h_m$. Here, flow enters from the right of the diagram.

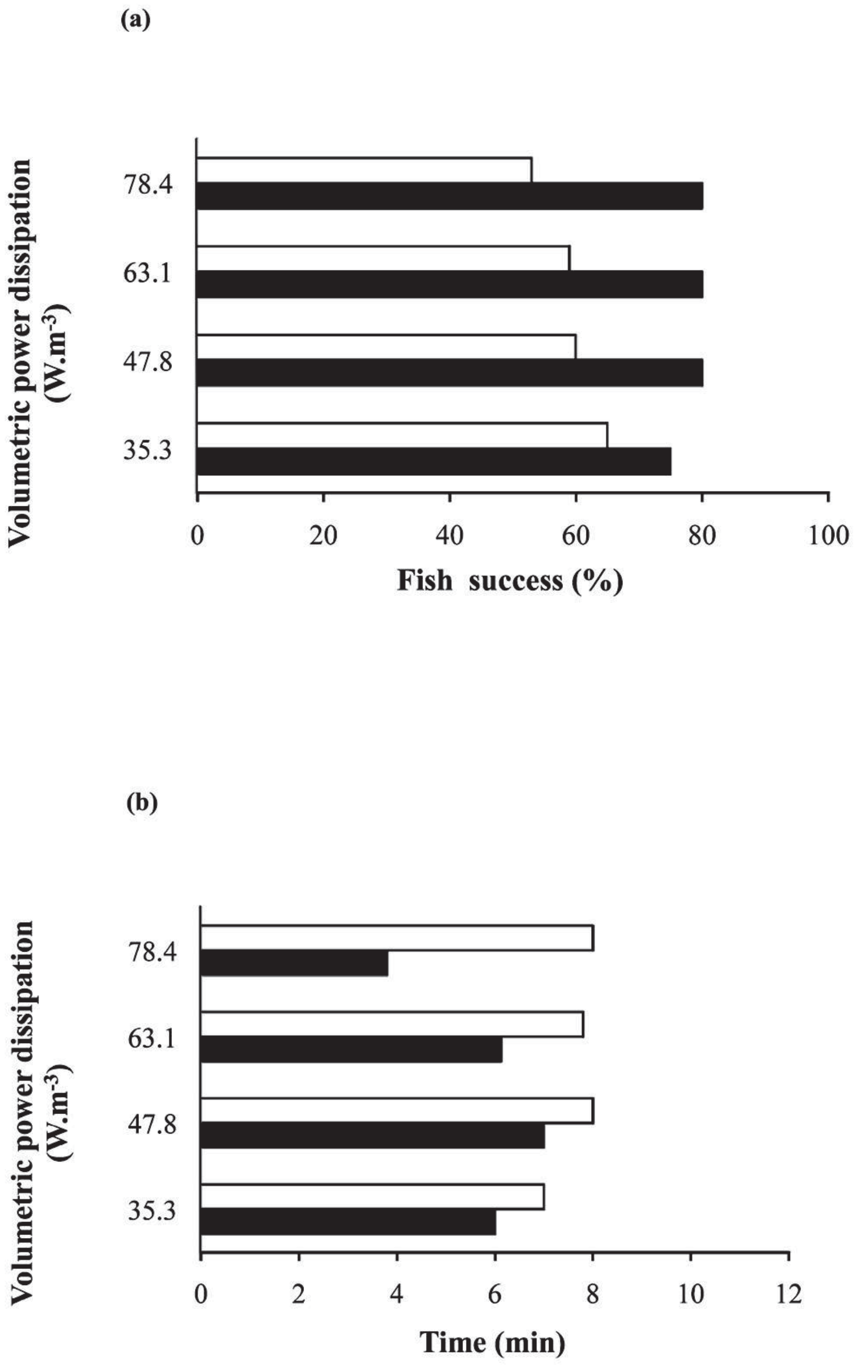

Fig. 3.6. (a) Percentage of fish that successfully negotiated the entire 6 pool fishway; (b) time taken by fish to negotiate the entire 6 pool fishway: small adults (15<TL<25 cm) (□) and large adults (25<TL< 35 cm) (■).

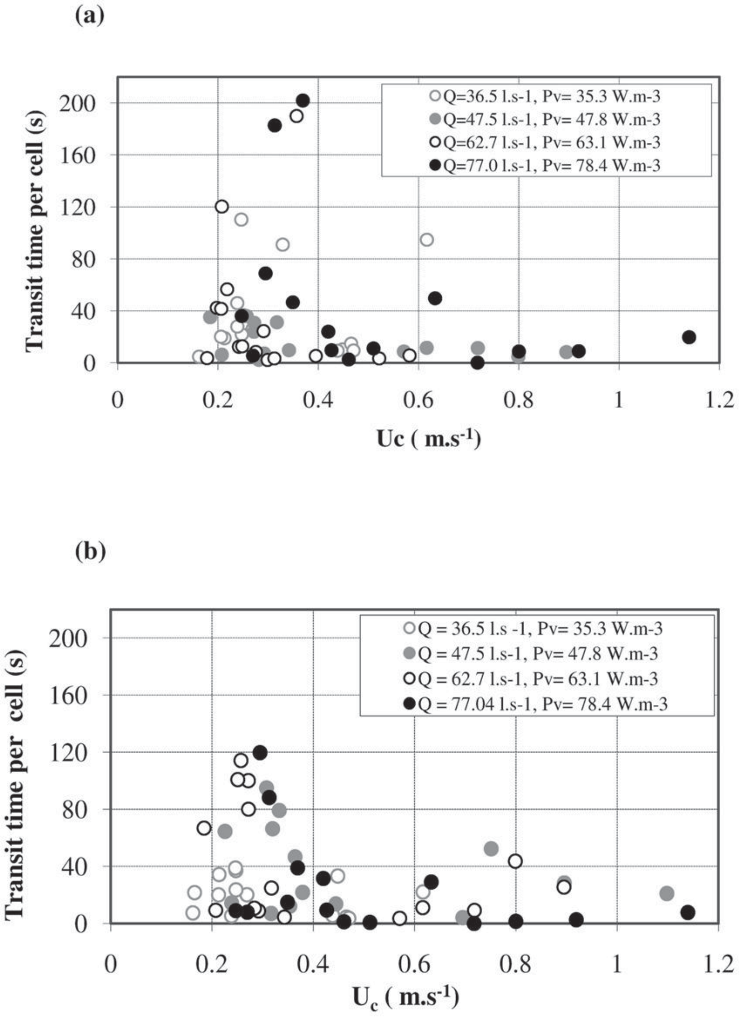

Fig. 3.7. Distribution of transit time per cell(s) versus mean velocity in each cell (U_c) at z = $0.25h_m$ for various tested discharges: (a) small adults (15<TL<25cm) and (b) large fish (25<TL<35cm).

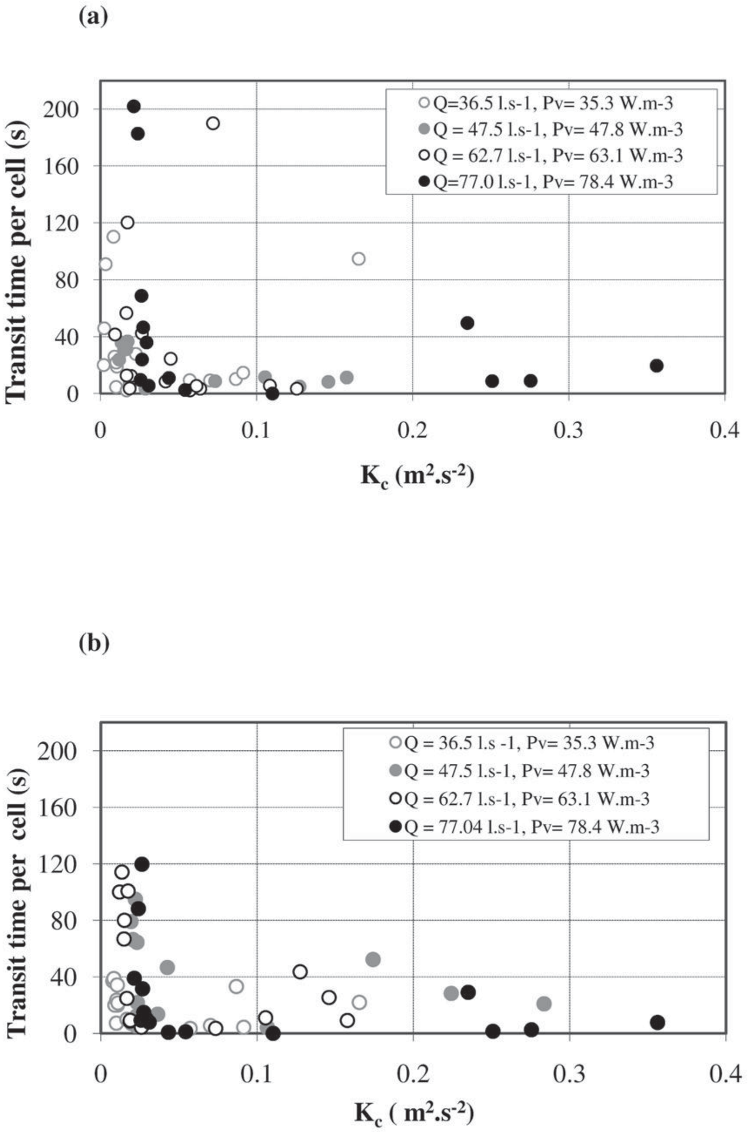

Fig. 3.8. Distribution of transit time per cell(s) versus mean turbulent kinetic energy in each cell (K_c) at $z = 0.25h_m$ for various tested discharges: (a) small fish (15<TL<25cm) and (b) large fish (25<TL<35cm).

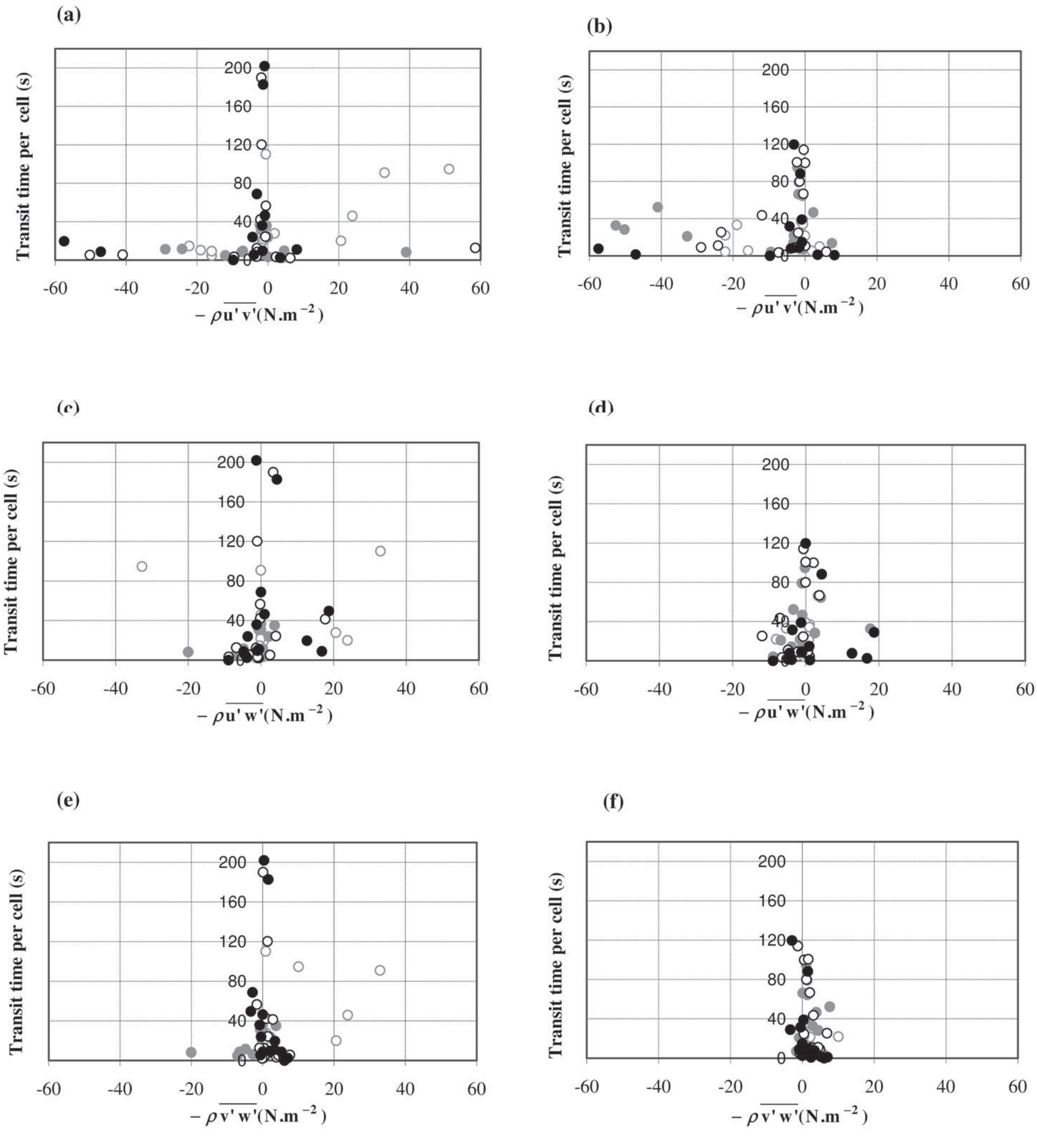

Fig. 3.9. Distribution of fish transit time per cell(s) versus Reynolds shear stress ($-\rho\overline{u'v'}_c$, $-\rho\overline{u'w'}_c$ and $-\rho\overline{v'w'}_c$) in each cell at z = 0.25 h$_m$: (a), (c), (e) respectively, for small adults (15<TL<25cm) and (b), (d), (f) respectively, for large fish (25<TL<35cm).

4. IBERIAN BARBEL (*LUCIOBARBUS BOCAGEI*, STEINDACHNER 1865) PREFERENCE FOR STRAIGHT OR OFFSET ORIFICES IN AN EXPERIMENTAL POOL-TYPE FISHWAY[3]

ABSTRACT

The effects of velocity and turbulence upon Iberian barbel's upwards movements in a pool-type fishways prototype, were studied. A total of 80 Iberian barbel were tested for different flow discharges (47.50 l/s to 71.70 l/s) and orifices alignment (straight and offset). Experiments were conducted with two adult fish (length: $15<TL<25$cm and $25 \leq TL<35$cm.). Pointwise measures of velocity were performed at 0.25, 0.50 and $0.80h_m$ by a 3D ADV and the turbulence parameters characterized. Differences on flow patterns were found for both experimental configurations leading to different fish behaviours. Offset orifices were observed to be far more suitable for fish upwards movement, mainly for large adults, which showed higher capacity to overcome the adverse hydraulic conditions existent within the fishway. Results revealed that Iberian barbel's behaviour was strongly tilting by turbulence action, in particularly by Reynolds Shear Stress tensions; pointing towards to the importance of regard this hydraulic parameter in future fishway designs.

KEY WORDS: cyprinids, pool-type fishway, offset orifices, straight orifices, upstream migration, fish size-class

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[3] Based on paper: Silva AT, Santos JM, Ferreira MT, Pinheiro AN, Katopodis C. (*submitted*). Iberian barbel (*Luciobarbus bocagei* Steindachner 1865), preference for straight or offset orifices in an experimental pool-type fishway. *Journal of Hydraulic Research.*.

4.1. INTRODUCTION

The free circulation of fish in rivers is often restricted by several obstacles of natural (rapids, waterfalls) or man-made (dams, watermills) origin, which obstruct fish upstream and downstream movements between specific habitats (spawning, foraging and refuge) greatly disrupting fish life cycle (Knaepkens *et al.*, 2005; Puertas *et al.*, 2004; Lucas and Baras, 2001; Cowx and Welcomme, 1998) particularly on those that complete their migrations within the river systems (Nicola *et al.*, 1996; Poulet, 2007). River fragmentation, caused by man-structures has then been considered as one of the most striking impact of human in Icthyofauna (Knaepkens *et al.*, 2007).The concept that both, river connectivity and the natural stocks of fish need to be preserve and enhance, has been recognized, leading to the development of hydraulic structures (fishways) that enable fish to overcome the river barriers (Katopodis *et al.*, 2005; Knaepkens *et al.*, 2006; Vasquez *et al.*, 2005). To develop a good fishways design suitable to the target species, the interplay between hydraulic and biological variables emerges as the key parameter in this process (Puertas *et al.*, 2004; Rodiguez *et al.*, 2006). Research has then been extensively developed focusing anadromous species due to their high economical value (Bunt *et al.* 1999; Baras *et al.*, 1994; Laine *et al.*, 2002; Gowans *et al.*, 2003; Katopodis 2005).Yet, very few information on coarse species behaviour within fishways has been available, particularly on cyprinids (Baras et al, 1994; Lucas and Frear, 1997), which can also travel considerable distances for reproduction, refuge and feeding purposes (Katopodis 2005; Lucas and Frear 1997; Ovidio and Philippart, 2002) and thus to be strongly affected by river barriers. A growing interest on research focused on the adaption of fishways for a variety of species, others than salmonids (Ead *et al.*, 2004), which greatly differ in their abilities to pass physical and hydraulic obstructions (Knaepkens *et al.*, 2005), has recently coming to light.

As in many other countries, the construction of fishways beneath the dimensional criteria suitable to salmonids (Larinier, 2002) is not an exception in Portugal , as well as the respective undesired results (Baras *et al.* 1994), consequence of the negligible existence of fishways that specifically target species others than salmonids. Fishways are commonly divided into four groups: pool and weir, Denil, vertical slot, and culvert fishway (Clay, 1995; Liu *et al*, 2006). The pool and weir fishways are the commonly used fish passage in Portugal (Santos *et al.*, 2005) which consist in a series of pools, arranged in a stepped pattern, separated by cross-walls that can be equipped with submerged orifices at the bottom, used to water flows. Fishway designs are thus, mainly focused to dissipate the energy in water, allowing fish to volitionally ascend the passage without undue stress (Avarez-Vázquez *et al.*, 2005). According to the biomechanics features of the species, fish rather swim over the weirs and orifices using their burst speed or jump the weirs (Ead *et al.*, 2004; Avarez-Vázquez *et al.* 2005). Considering that Portuguese fish fauna ranges from small-size, bottom-dwelling species to large-size long distance migrants, exhibiting a variety of ecological requirements (Santos *et al.*, 2005), the need of develop suitable dimensional criteria of fishways to lowland fish species in Iberian rivers is thus utterly recognized and understandable (Stuart and Mallen-Cooper, 1999; Katopodis 2005).

The Iberian barbel *Luciobarbus bocagei* (Steindachner, 1864) is one of the most representative species in Iberian rivers (Geraldes *et al.*, 1993; Santos *et al.*, 2005) which has been target of recent studies focused in its migration ecology (Capel and García de Jalón, 1999). Although a small numbers of studies have addressed the Iberian barbel's behavioural response to the hydraulic characteristics existent within a fishway, such as water velocity and turbulence. As a rheostatic species, the Iberian barbel's behaviour tends to be orientated to water current. This orientation is an important and widespread behaviour in fish, strongly evident in their upstream migrations. This can be mediate by a plethora of sensorial cues which importance varies with circumstances (Montgomery *et al.*, 1997). Rheostaxis is therefore mediated by visual and tactile cues by hydrodynamic receptors as the existents in the lateral line of fish (Montgomery *et al.*, 1997). Nevertheless, the mechanism of velocity and turbulence impact on fish behaviour still remains poorly understood. It is of general understood that velocity and turbulence do play an essential role in fish' balance capacity and consequently in their swimming performance (Lupandin, 2005; Rajaratnam *et al*, 1998). What has clearly been proved in several studies (Odeh *et al.*, 2002; Pavlov *et al.*, 2000; Enders *et a*l., 2003), by the volitional avoidance behaviour of fish for areas with high velocities (Odeh *et al.*, 2002). As a factor of hydrodynamic heterogeneity of fish environment, turbulence effects on fish varied according with the time of exposure and size of the turbulence fluctuations (turbulence scale) (Odeh *et al.*, 2002). Studies focusing on the impact of such hydraulic variable on fish behaviour have been developed (Lupandin 2005; Cotel *et al.*, 2006; Odeh *et al.*, 2002) but still, little information is available for coarse-fish (Rajaratnam *et al.*, 1988; Odeh *et al.* 2002).Thus, the need of developing studies aiming to understand how Iberian barbel sense, react and use the hydraulic phenomena in their upwards movements, aiming the development of valuable guidelines for future fishway designs, is clear.

Likewise in a natural river, in laboratory test apparatus flows are turbulent (Vogel, 1994) and therefore turbulence effects on fish can be produced and measured under laboratory settings (Odeh *et al.* 2002). Owing to the plethora of interacting factors existent under natural environment, laboratory conditions, in which the variables of interest can be manipulated, appear as an excellent opportunity to gain generic insights into fish behaviour (Kemp *et al.*, 2006).

This experimental study was thus undertaken in an experimental pool-type prototype to characterize the turbulent flow for various experimental configurations and analyse how the hydraulic characteristics influence the Iberian barbel navigation within this hydraulic device.

4.2. MATERIALS AND METHODS

Fishway apparatus

Figure 4.1 shows the experimental full-scale pool-type fishway used, installed at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon. The structure comprised a rectangular flume with 10.0.m long, 1.0 m wide and 1.20 m high, externally reinforced by a steel frame with fiberglass sidewalls. The flume's bottom was made smooth, straight and level to avoid the formation of eddies (macroturbulence). Six pools; 1.0 m wide per 1.2 m high with a length of 1.9 m; were created by five PVC made cross-walls, each equipped with a submerged orifice of adjustable area. Two fishway experimental designs were tested, varying on the arrangement of consecutives orifices: Type I) orifices positioned in an offset way, Type II) orifices positioned in a straight way, (Figure 4.2). The flume was set at a slope of 8.5%, within the range of those commonly used in this type of hydraulic devices (Larinier, 2002). The structure also encompassed two concrete tanks, located at the upstream and downstream end of the flume, with 2.6 m long x 1.0 m wide x 1.2 m high and 4.0 m long x 3.0 m wide x 4.0 m high, respectively. The first tank provided a smooth flow entering in the flume, whilst the second was used as an acclimation chamber for fish, which was separated from the main structure by a mesh panel (Figure 4.1). Water used in the experiments was drawn from domestic water supply (soft water) and was pumped from the laboratory pumping system into the upstream tank. Two pumps were used to supply the required discharge up to a maximum of 250 $l.s^{-1}$. This system was also used to recirculation of the water for at least two weeks prior to the experiments, ensuring throughout dechlorination and "maturation" (Copp *et al.*, 1998). At the beginning and at the end of each trial the water was checked for temperature, hardness, pH and dissolved oxygen by using of a multiparametric probe (Hydrolab, Quanta model). Flow discharge was measured and controlled by magnetic flow meters located in the supply lines and a flow control valve located at the upstream tank, whilst the water level within the flume was regulated by an adjustable control slot gate at the downstream end of the fishway. The structure was assuming a uniform flow (i.e. identical depth at equivalent points with each of the six pools) leading to a constant head drop (Δh) between two consecutive pools of 0.16 m generating a maximum flow velocity of 1.77 m.s^{-1}, based calculation in formula $V_o = \sqrt{2g\Delta h}$ = 1.77 m.s^{-1}, where *g* is the acceleration due to gravity, 9.80 m.s^{-2} (Larinier, 2002).

To guarantee uniformed lighting around the structure of the flume a tarpaulin was erected at 4 m above and laterally to the flume which gave unimpeded observation from sunlight reflection. The structure was illuminated by the lighting system of the laboratory.

Hydraulic measurements

Four set of experiments were conducted, varying on flow discharges (Q) (47.50 l.s^{-1} to 71.70 l.s^{-1}), submerged orifices areas (A_o) (0.03 m^2 to 0.05 m^2) and orifice arrangement (straight and offset) as well as volumetric dissipated power (P_v) (47.20 W.m^{-3} to 62.70 W.m^{-3}) (Table 4.1). The selection of these hydraulic designs, was based in a prior experimental study, designed to assess the selection of Iberian barbel for submerged orifices or notches in a pool-type fishway (Silva *et al.*, 2009), in which, results showed that fish preferentially use submerged orifices to ascend the passage.

Extensive pointwise measurements of the three-dimensional velocity components (x, y, and z) of flowing water were made in the flume to characterize the flow fields through which fish would have to swim in the four experimental designs. Data was acquired by a 3D Acoustic Doppler Velocimeter (ADV) oriented vertically down (Nortek AS) at sampling rates of 25 Hz. The advantage of using this device relies on its ability to adequately measure the three-dimensional velocity components (x, y, z) of flowing water (Papanicolaou and Maxwell, 2000; Odeh *et al.*, 2002; Ead *et al.*, 2004; Guiny *et al.*, 2003).To establish the sampling period needed for an accurate determination of the mean velocity and turbulence parameters, previous velocity measurements were carried out. The ADV was consequently tested for sampling periods ranging between 5 to 350s, have been found that above 30s velocity became almost constant. Taking into consideration that the sampling period required to provide converged statistic of mean and turbulence features is controls by the mean velocity (Liu *et al.*, 2006), a sampling period of 90s was chosen.). Measurements were taken in the 2nd downstream pool; considered representative of the hydraulic conditions existents within the fishway, at different horizontal planes parallel to the flume bottom, at 25%, 50% and 80% of the pool mean depth (h_m). In each plane, a predefined grid of 48 measurements points distributed according to the velocities fluctuations expected was used as reference. On the whole, 2500 instantaneous measures were recorded for each sample point.

To characterize the hydraulic conditions within the pool for each of the four experiments, the velocities fields were described and analyzed at the different planes (XY, XZ and YZ), and the ratios between the maximum velocity in each plane (Vxy_m, Vxz_m and Vyz_m) and the maximum flow velocity at the orifice (V_o) calculated.

It is known that turbulence can have a strong impact on fish's swimming capacity (Silva *et al.*, unpublished; Puertas *et al.,* 2004; Odeh *et al.*, 2002), being commonly quantified in studies using fish (Cotel *et al.*, 2006) .Turbulent parameters (turbulent kinetic energy K, turbulence intensity TI, and Reynolds shear stress) were then calculated based on the instantaneous velocities (V_t) measurements, which can be decomposed as:

$$V(t)=\overline{V}+V'(t) \tag{4.1}$$

where $\overline{V}$ is the mean velocity in the point during the sampling period and *V'(t)* is the fluctuating component of velocity at sampling time t. The root mean square for fluctuating velocity component is a measure of velocity intensity and it was calculated for the longitudinal component (*u*') by:

$$\overline{u'}=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(u_i-\overline{U}\right)^2} \tag{4.2}$$

where *u'* is the longitudinal fluctuating component of *V'(i)*, $\overline{U}$ the mean longitudinal velocity in the point for the sampling period and *n* is the number of instantaneous velocity measurements. Also the transversal and vertical components of *V'(i)*, v' and w' respectively, were calculated.

The turbulent kinetic energy (*K*), which corresponds to the kinetic energy associated to the fluctuating velocity at a given point (Rodi, 1980), was calculated by:

$$K=\frac{1}{2}\left(\overline{u'}^2+\overline{v'}^2+\overline{w'}^2\right) \tag{4.3}$$

where, $\overline{u'}$, $\overline{v'}$ and $\overline{w'}$ are root means square values of the fluctuating components of *V'(t)* on the system of coordinates *x, y, z.*

Attempting to generalize the results for situations others than the ones tested, turbulent kinetic energy was created dimensionless using the maximum velocity in the orifice (V_o), according to:

$$\kappa = K^{0.5}{}_{m} / V_o \qquad (4.4)$$

Turbulence intensity (*TI*), which quantified turbulence in terms of the magnitude of the turbulent fluctuations about the average velocity at a given location over the period of measurement (Odeh *et al.*, 2002; Cotel *et al.*, 2006; Nietzel *et al.* 2000), was also calculated based on the following equation:

$$\mathrm{TI} = \frac{\mathrm{K}}{\overline{\mathrm{V}}^2} \qquad (4.5)$$

Reynolds shear stress is considered as one of the most important hydraulic parameters determining fish behaviour (Odeh *et al*, 2002). It is defined as force acting parallel to fish body whilst fish passage between two water masses of different velocities (Gordon *et al*, 1992), was determined for XY plane, by:

$$-\rho\overline{u'v'} \qquad (4.6)$$

where ρ is the water density, u' and v' are the fluctuating velocities in X and Y directions, respectively. The exclusion of the analyse of Reynolds shear stress at XZ and YZ plane in this work was set in previous results (Silva *et al.*, unpublished), in which fish were found to be more effected by the tensions of Reynolds shear stress acting in the XY plane when compared with the ones exercise the XZ and YZ.

This hydraulic parameter was created dimensionless using the maximum velocity in the orifice (V_o), according to the following equation, for the XY plane:

$$\overline{(-u'v')_m} / V_o^2 \qquad (4.7)$$

where the subscript *m* refers the maximum value in a horizontal profile, to z = 0.25h$_m$ and z = 0.80h$_m$.

Biological experiments

A total of 80 adult Iberian barbel (*Barbus bocagei*) were collected at the river Nabão, a tributary of the river Zêzere (central Portugal) on May 2008. Capture was performed by means of electrofishing (Electrocatch International, Sarel model WFC7_HV, Wolverhampton, UK) using low voltage (250 v) and a 30 cm diameter anode. Fish sampling took place during barbel's natural reproductive migration season, which generally occurs from April-June (Santos *et al.*, 2005). Merely, adult fish were selected to test, what was carried out by in *situ* macroscopic observations of fish gonads development stage, particularly their volume, vascular irrigation and visibility of oocytes, and presence of nuptial tubercles (Agostinho *et* *al.*, 2007). Fish were brought to the laboratory and measured for total length (TL). To test for size-related differences in species behaviour, according with their size, fish were separated into two size-classes: small (15 < Total length (TL) < 25 cm: n= 40, mean 19.35, SD 2.24) and large adults (25 ≤ TL < 35 cm: n= 40, mean 28.19, SD 3.32). Iberian barbel of each size-class were then held for one week in four tanks (length x width x height = 1.45 x 0.70 x 0.80 m) at a density of 20 per tank, to recover from the capture and transport processes. Water quality within tanks was insured by an ELITE aerator systems and mechanical filters. During this period, fish were daily feeding with pond sticks (Tetra Pond), until 24 h prior to experimentation. The room was temperature controlled, thus the water in tanks and in the fishway was maintained at 18 ± 2ºC.

Fish experiments were conducted between 19 of May and 9 of June 2008, under the four previously tested hydraulic conditions (Table 4.1), each consisting of 10 replicas. Fish were tested for periods of 1.5 hours from 17h00 to 19h30, to encourage attempts by this species which typically migrates at dusk (Santos *et al.*, 2005). Each trial was accomplished with two adult fish, one of each size-class, which were randomly selected from the thanks and introduced in the acclimation chamber where they remained for 12 hours prior to experimentation and were prevented from entering the flume by mesh panel (Figure 4.1). Once the flow discharge in the flume was brought to the desired level, the mesh panels were removed and fish were allowed to ascend the fishway of their own volition. During a trial, fish behaviour was continuously monitored through the glass sidewalls of the fishway by means of direct observation, carried out from two operators at 1 m distance from the flume. Each of whom, followed a single fish registering all of its movements, including the time taken by the fish to enter the flume and to ascend from one pool to the next one. Video records of barbel' behaviour was also assessed for ach trial to supplement the former observations. This consisted in three digital video cameras focused on the second pool; of which two of them were positioned at 2 m from both side-walls of the pool and one at 3 m above the water surface. Aiming to aid video analyses, a 1.90 x 1.00 m reference grid containing 15 contiguous sequentially numbered cells (each 0.38 x 0.33 m) was created and placed above the second pool. Video records were analyzed using the IVision Labview software from National Instruments (http://www.ni.com), allowing the collection of continuous fish exact locations within the pool. This procedure was accomplished by one only operator. The position of a fish within the pool as its time in each cell (transit time) was then determined. A fish was considered to occupy one cell, when more then half of its body length was within a cell's boundaries.

Statistic analyses

Kruskal-Wallis ANOVA test was used to compare the TI and the transit times in each cell among experiments. To test for correlations between transit time and mean velocity, turbulent kinetic energy, turbulence intensity and Reynolds Shear Stress, the Spearman rank coefficient was used. Owing to the preferential remain of fish close to the bottom of the fishway, analyses were performed using data collected at $z = 0.25h_m$ instead of considering mean values obtained from all the three planes. The statistical procedure was performed with the Statistic program (version 6.0).

4.3. RESULTS

Flow patterns and velocity distribution

The flow patterns were found to be more stable in response to variation in discharge than in the pool experimental design. Although the three-dimensionality of the flow, characteristic of pool-type fishways (Puertas *et al.*, 2004), in all the tested configurations flow showed to be essentially bidimensional, i.e. from the three velocity directions (X, Y and Z), flow velocity was found to be higher at X and Y directions. Figure 4.3, shows the three-dimensional schematic flow patterns within the pool for straight and offset configurations at Q= 47.50 $l.s^{-1}$ and Q = 50.50 $l.s^{-1}$. It is clear that flow velocity strongly varies with depth, decreasing drastically with the proximity to the water surface. In the deeper level, at 0.25 h_m, two different regions can be clearly distinguished in both designs: a primary flow, which travels from one orifice to the next with high velocities and a recirculation region with low velocities. Between offset orifices, the primary flow travels towards the sidewall and the opposite cross-wall until the next orifice, with maximum velocities of 1.520 $m.s^{-1}$ at a roughly distance of 0.30 m downstream from the cross-wall (Figure 4.3a). Opposite to this a large recirculation region characterized by low velocities (mean ± S.D ($m.s^{-1}$): 0.27 ± 5.39) and reversed flow directions is created. The primary flow amid two aligns orifices, travels directly between them, next to the sidewall adjacent to the inlet water orifice , reaching to 1.58 $m.s^{-1}$ (Figure 4.3b), at the vicinity of this. Opponent to the main flow, velocity drastically decreases creating an area of low velocities suitable for fish rest *"resting-areas"* (mean ± S.D ($m.s^{-1}$): 0.21 ± 4.30) (Figure 4.3b). In both designs, near the surface ($z = 0.80\ h_m$), a recirculation flow (counter-clockwise) was observed with negligible velocities. This vertical variation of velocity was found to be stronger in experiments conducted with align orifices (Figure 4.4a).

Differences on velocities within the same experimental designs were also observed, increasing in response to a rising flow (Figure 4.4a). Longitudinally (XZ plane), in all the experiments, maximum velocities were found in the vicinity of the side-wall adjacent to the upstream orifice decreasing towards the opposite side-wall, creating the so-called "*resting areas*" suitable for fish (Figure 4.4b). Herein, velocities throughout the pool were also superior in experiments conducted with higher flow discharges, peaking at 0.86 of V_o. Transversally (YZ plane), the maximum velocities slightly varied with the increasing discharge, peaking in the vicinity of both cross-walls ±.40 V_o, ranging between 20 to 30 V_o in the remaining areas (Figure 4.4c).

Turbulent kinetic energy

The vertical variation of the maximum dimensionless turbulent kinetic energy (K) in the pool for all the experiments is shown in the Figure 4.5. It is clear that turbulent kinetic energy is higher near the bottom of the flume ($z = 0.25h_m$) varying between 0.3-0.5 of V_o, increasing with flow discharge. With the proximity to water surface, κ drastically decreases to particularly low values (around 0.1 and 0.2 of V_o), being smaller in the experiments conducted with align orifices. The contours of the mean dimensionless maximum turbulent kinetic energy ($Q= 47.50 \text{ l.s}^{-1}$ and $Q = 50.50 \text{ l.s}^{-1}$) at $z = 0.25h_m$, and $z = 0.80h_m$ are plotted in Figure 4.6. For both configurations, κ was found to be higher along the streamline between the submerged orifices (>0.16 V_o), decreasing transversally, creating reasonably recirculation areas of small κ (below 0.08 $V_{,o}$) desirable for fish rest, which were slightly smaller in the second experimental design (Figure 4.6b). These patterns didn't differ significantly between both design configurations. In contrast, near the surface, κ was smaller and remained almost constant, mostly in experiments developed beneath the second design configuration in which κ was less than 0.08 in or so 80% of the area of the pool.

Turbulence intensity

Figure 4.7, shows the variation of the maximum Turbulence intensity (TI) with water depth (z/h_m). It can be observed that, in all the experiments, TI is higher nearby the surface ($z = 0.80h_m$) ranging approximately between 0.6 and 0.8, increasing with flow discharge. In figure 4.8, the contours of the mean TI for $Q = 47.5 \text{ l.s}^{-1}$ and $Q = 50.5 \text{ l.s}^{-1}$ at $z=0.25h_m$, and $z=0.80h_m$ are shown. Herein, it's clear that the patterns of distribution of TI differ between the two experimental design, although no statistic significance were found (Kruskal-Wallis

ANOVA: p>0.05). In the first configuration at $z = 0.25h_m$, TI predominantly remains below 0.3 (Figure 4.8a) slightly increasing with the proximity to water surface ($z = 0.80h_m$) (Figure 4.8b). Higher values of TI can be seen near the bottom of the flume in the second configuration (Figure 4.8c), configuration, herein near the surface ($z=0.80h_m$) in more than 80% of this plane TI ranged between 0.3 and 0.6 (Figure 4.8d). Regardless the experimental design, maximum values of TI were always observed in recirculation areas, characterized by low current speed (Figure 4.3), suggesting that turbulence intensity tends to decrease with the increase of water velocity (Cotel *et al.*, 2006) .

Reynolds shear stress

Analogous to the variation of velocity and turbulent kinetic energy, Reynolds shear stress was found to respond directly to the increment of flow discharge and water depth (Figure 4.9a). Also, in all the experiments the highest values were found close to the bottom of the flume, peaking at $0.06V_{o.}$for the highest flow discharge tested. Near the surface, at $z = 0.80h_m$, this tension was rather lower, ranging between -0.01 and 0.02 of V_o. In Figure 4.9b, the variations of dimensionless maximum Reynolds shear stress in the XY $(\overline{(-\rho u'v')}_m / V_o^2)$ across the pool (y/B) for all the experiments at $z = 0.25h_m$ are plotted. It can be seen that Reynolds shear stress is greater in the main flow region ($0< y/B <0.5$) varying between 0 and 0.02, particularly in experiments conducted with straight orifices. In these, Reynolds shear stress decreased from the middle part of the pool ($y/B >0.5$), remaining at very small values in the recirculation's areas, varying between -0.01 and 0.01. Likewise, in experiments with offset orifices, smaller values in the recirculation area; nonetheless, at the vicinity of the side-wall opposite to the flow inlet, Reynolds shear stress increased reaching to values between -0.01 and -0.03. This pattern was clearly evident in experiments with higher flow discharges.

Fish behaviour

Out of a total of 80 barbel tested (small fish: 40, large fish: 40), 38 individuals (48%) reached the top of the fishway (success): 16 with 15<TL<25cm (20%) and 22 with 25≤TL<35cm (28%). Overall, large fish presented a higher rate of success (55%) in ascending the fishway relatively to small adults (40%).This was mostly evident in experiments conducted with offset orifices, in which the highest rate of success was observed (mean = 68%): or so 80% for large fish and 55% for small fish (Figure 4.10a). In opposite, in experiments conducted with align orifices the rate of success was low (mean = 28%) and the influence of fish dimension seemed to be less evident since only 30% of large fish and 25% of small fish successfully passed the fishways (Figure 4.10b). Also, in all the experiments, large adults took less time to ascend the fishway (mean ± SE (min): 6.05 ± 0.42), when compared to small-size individuals (mean ± SE (min): 9.25 ± 0.73) (Figure 4.10b). It is clear, that small fish barely negotiated the hydraulic conditions existent within experiments conducted with align orifices, taking longer to reach the end of the fishway (mean ± SE (min): 13.2 ± 1.43) when compared with the time taken in experiments with offset orifices (mean ± SE (min): 7.45 ± 0.82). Large fish seemed to easier negotiate the adverse hydraulic conditions existent, taken rather less time to successfully pass the fishway: (mean ± SE (min): 3.33 ± 0.59) in experiments conducted beneath align orifices and (mean ± SE (min): 7.06 ± 0.50) in experiments with offset orifice. In all the experiments, fish remain preferentially near the bottom of the flume, exhibiting behaviour virtually to the one observed under natural conditions (Capel and Garcia de Jalón, 1999). Although, fish were found to explore the water column, just to approach the orifices, avoiding the high velocities of the main flow, mostly in experiments conducted with align orifices.

The hydraulic characteristics in the first configuration (offset orifices), seem likely to be the most suitable to fish negotiate the fishway, leading to the exploration of the different hydraulic regions created in a pool. Thus, in this configuration, fish tended to remain longer within the pool (total of 2061.93 s), particularly large fish which spent more time in this (1226.46 s), when compared with small fish (835.47 s). The strongest rheostatic behaviour of small barbel (Capel and Garcia de Jalon, 1999) is herein clearly evident. Due to the smoothest hydraulic conditions existent in the *resting-areas* (Table 4.2), fish tended to mainly remain on these, so 90% and 86% of the total of time spent within a pool by small and large adults, respectively, was used to explore those areas. In the second experimental configuration, fish of both size-classes showed to barely negotiate the conditions existents (Table 4.2), in which the high velocities and turbulence of the main flow showed to strongly hinder fish upstream movements, raising the likelihood of fish been dragged downstream resulting in small times of permanence within the pool (total of 789.89 s). Small adults' upstream movements seemed to be the most affected by the hydraulic conditions, ensuing in longer times of permanence inside of the pool (454.22 s) of which 74% was spent in areas of low velocities (Table 4.2). Large fish showed to easier overcome the hydraulic conditions existents, permanence less time in the pool (335.37 s), exhibiting a highest resilience facing up adverse environments. During this period, fish spent nearly times attempting to negotiate the high velocities existent in the main flow (172.59 s, 51%) and resting in the recirculation area (162.78, 49%). No, significant differences on transit time in each cell among experiments were found (Kruskal-Wallis ANOVA: $p>0.05$).

As rheostatic species, fish showed to be attract by current speed as shown by fish attempts to swim again high velocities in their upward movements. Nevertheless a negative correlation was found between the transit time and the mean velocity, which was highly evident in experiments conducted under the first configuration, mostly for small adults (Table 4.3). Also, a strong significant negative correlation between turbulent kinetic energy and fish transit time in each cell was found for both fish sizes, had been clearly higher for small adults (Table 4.3). Still in this experimental design, a relation between fish transit time and turbulence intensity was found. Heavy correlations were also found between small fish' transit time in each cell and Reynolds shear stress (Table 4.3), pointing towards that fish's movements are highly oriented by this hydraulic variable, which seemed to have played an important role on fish behaviour. In Type II design, no significant relations were found among fish transit time in each cell and the hydraulic variables studied (Table 4.3). The high velocity and turbulence associated to this design, seemed to have had compromised fish movements and balance. In high turbulent zones, visual observations demonstrated dorsoventral oscillatory movements of the fish, with a consequent strong disorientation and displacement in all angles, including inverted, increasing the likelihood of fish to overturn and be dragged downstream. Attempting to stabilize and sharply increase the hydraulic resistance of their body, fish were finding to spread their pectoral fins decreasing this way their swimming capacity.

4.4. DISCUSSION

Herein, an understanding of the existing flow patterns, velocities and turbulence in two different hydraulic configurations in an experimental pool-type fishway was analyzed and studied in terms of suitability to Iberian barbel's upstream movements, considering the swimming capacities and biological requirements of this species. The interplay between hydraulic and biological variables was therefore approached, which is considered as one of the major problems inherent to fishway design and which study is a notorious difficult challenge (Bunt *et al.*, 1999), had been this study no exception. As many others laboratory studies (Guiny *et al.,* 2003) this work proved to be a powerful tool to knowledge improvement in the design of fishway in view of adapting the dimensional criteria of this facilities to target species. The development of the latter require appropriate physiological conditions of fish to non-compulsory swim upstream as well as adequate hydraulic conditions. Also, to avoid the likelihood of biased conclusions, experimentation should be performed under conditions virtually to the existents in the natural habitat (Castro-Santos, 2004). Results showed that both experimental designs were well balanced in terms of hydraulics, with values were within the range of those commonly used in this type of hydraulic devices, specifically for cyprinids (Larinier, 2008). In addition, no odd behaviour or physical alterations were found throughout the experimental period, pointing to no unnatural behaviour caused by operational procedures.

The high rate of success found in the first design (mean = 68%) in detriment to the second design (mean = 28%), clearly evidence that the latter design is not suitable for barbel's upwards movements. Although, at $z = 0.25\ h_m$, in this configuration the rest areas are undoubtedly bigger when compared with the ones observed in the first configuration, the aggressive direct primary flow characterized by high velocities, seemed to have strongly hindered fish' upstream movements, which barely negotiate the adverse hydraulic conditions existents. The abrupt longitudinal stratification of velocity existent in the second experimental design can be possible seen as one of the major problems of this configuration for fish mobility, mainly for small fish as shown by the low rate of success added to a long time to ascend the passage. Likewise other studies (Slavik et al, 2009; Silva et al, unpublished) the importance of fish size as one of the major determinants factors of fish capacity to face adverse hydraulic conditions in a fish ladder, was evident.

Whilst under the natural habitat, fish usually are confronted with the need to get to compromises among many interacting physical and biotic factors (Slavik *et al.*, 2009; Cotel *et al.*, 2006) attempting to achieve stability in a specific location. Although it is function of perturbation magnitude, stability which implies the ability to control posture and location in water column, is also dependent on the momentum (Cotel *et al.*, 2006) and therefore on the hydraulic parameter's fluctuations, as velocity a turbulence (Bunt, 2001; Odeh *et al.*, 2002; Lupandin, 2005). Results evidence that Iberian barbel's behaviour and the respective patterns of distribution within the passage are clearly reflection from the former relation. Regardless, fish dimension, it is unquestionably that fish spent more time in areas with low velocities, as shown by a higher negative correlation coefficient between this parameter and fish transit time for the experiments in the first experimental design. Although, in experiments conducted with align orifices, no relation have been established between water velocity and transit time, the impact of water velocity in fish behaviour still clear. The absence of such correlation can be interpreted as the result of the strong longitudinal stratification mentioned before. Several studies have shown that fish tend to use the maximum critical swimming speed when crossing the cross-walls (Larinier, 2002; Odehe *et al*., 2002; Mateus *et al*., 2008) followed by a decrease of swimming velocity, leading to an intern equilibrium of energy which aid fish to negotiate the hydraulic conditions with a minimum energy expenditure (Pavlov *et al*., 2000). Nevertheless, due to the high velocities in the primary flow and the additional energy expenditure required for fish balance control in such adverse condition, both, fish swimming capacity and the likelihood to achieve an equilibrium point decreased, leading to the observed fish disorientation and constant displacement even in areas with low velocity.

The effects of turbulence kinetic energy (K) on fish behaviour were extremely pronounced, clearly evident through the high negative correlations found between this hydraulic parameter and transit time as well as by the apparent disorientation of fish whilst attempting to swim in turbulent flow. This phenomenon was mainly noticeable in experiments conducted with align orifices, particularly in small adults. Fish-size effect on fish swimming capacity was therefore evident, pointing towards that high turbulence is necessary to decrease the critical flow rate of longer fish (Lupandin, 2005). It is of general understanding that the impact of turbulence on fish's swimming capacity strongly varies according to the shape and size of turbulence vortex (turbulence scale) exercised on fish body (Lupandin, 2005; Odeh *et al*, 2002). Therefore, the observed fish orientation at all angles, including inverted can be explain as the result of the impact of the vortex structure of turbulence on fish body, which disturbs fish balance (Lupandin, 2005). Adding the limited swimming capacity of this species (Doadrio, 2001) and the high energy expenditure required by fish to maintain its balance in turbulent flow condition (Pavlov *et al*., 2000), all these factors can be recognized as the main reasons to the prominent occurrence of fish in areas with low velocities and turbulence. Nevertheless, it is known that beneath low turbulence environments, fish locomotion indices of rheoreaction tend to decrease (Lupandin, 2005), resulting in higher times of permanence in areas with low turbulence. This phenomena was mainly observed in the second experimental design in which fish seemed to become “trapped” in those areas, compromising fish’ upwards movements, increasing therefore the time spent within the pool (Tarrade *et al*., 2008)

It is known that in speed currents, TI tends to be lower, leading to a decrease in the control of stability (Cotel *et al.* 2006). Therefore it would be expected that fish preferentially occupied areas with high TI values, what was not evident in this study, in which barbel were mainly found in areas with low to medium TI. This can be owing to the fact that the highest TI have been observed towards the water surface and the lowest at the bottom, where fish remained. The fish-size effect also observed for TI suggest that like K, TI is an appropriate measure of turbulence impact on fish, mainly in terms of stability. The low capacity of small fish to achieve equilibrium even in medium TI conditions can thus be interpreted as the result of the impact of the hydrodynamic forces associated to turbulence on fish body (Cotel *et al.*, 2006).

Likewise K and TI, Reynolds Shear Stress is a turbulence parameter with great impact on fish behaviour. As shown by the high correlations between fish transit time and Reynolds shear stress on the XY plane ($\overline{-\rho u'v'_c}$), found in the first experimental design. This result, as shown in others studies (Silva *et al.*, 2009 unpublished, Odeh *et al.*, 2002), points towards to the importance of Reynolds shear stress as key-parameter determinant of fish' movements within a pool-type fishways. The effects of this parameter on fish vary according to the intensity of which it is applied as well as with the target species, whose sensitivity to strain is different. It is known that within confined man-made structures such as submerged orifices of pool-type fishways high and potentially undesirable values of shear stress can occur (Cada *et al.*, 2006). High Reynolds Shear Stress might cause injuries or even mortalities (Nietzel *et al.*, 2000), which typically occur at much higher levels ($\geq$ 700 N.m^{-2}) (Cada *et al.*, 1999). The absence of any type of injuries in the tested fish indicates that shear stress existent within the experimental conditions were suitable for this species swimming capacity, dovetailing in the range of the estimates values in a medium-size stream ($\leq$ 30 N.m^{-2}). Likewise to the other hydraulic parameters, the latter was found to have greater impact on smaller-size individuals' behaviour. Fish-size effect was well evident throughout this study highlighting the importance of considering different size-classes whilst studying the effects of hydraulics variables on fish,as shown by Slavick *et al.*, 2009.

The finding results suggest that a pool-type fishway seems to be a suitable facility to free instream movement of Iberian barbel. As one of the few studies evaluating fish pass performance for small bottom dwelling, the results found in this study might provide basis for further research, namely concerning the design of fishways for "weak" swimmers. The utterly orientation of fish movements by the hydraulic conditions existent within the fishway, in particularly by turbulent kinetic energy and Reynolds shear stress, reveals that especially noteworthy should be taken to these hydraulics parameters whilst the development of a fishway design. Detailed research focusing potential adaptation of design configurations, aiming to reduce the former hydraulic variables minimising the impact of these on fish behaviour, mainly in small benthic species, is therefore extremely necessary. The incorporation of advanced tagging and retrieving techniques in such studies, could seriously contribute to advance the knowledge of species behavioural patterns during obstacle negotiation with different hydraulic conditions.

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Table 4.1. Summary of the experimental designs for hydraulic characterization: submerged orifices area (A_o), head drop between pools (Δh), volumetric power dissipation (P_v), pool mean water depth at 25, 50 and 80%. Fish sizes of individuals used in the experiments are also shown.

Design	Orifices alignment	Exp.	Variables											
			A_o (m^2)	Δh (m)	Q ($l.s^{-1}$)	P_v ($W.m^{-3}$)	h_m (m)	25% h_m (m)	50% h_m (m)	80% h_m (m)	Small fish: 15<TL<25cm		Large fish: 25≤ TL<35cm	
											N	Mean ± SD (cm)	N	Mean ± SD (cm)
Type I	offset	E1	0.04	0.16	47.5	47.80	0.86	0.21	0.43	0.68	10	19.85 ± 2.49	10	28.44 ± 3.11
Type I	offset	E2	0.05	0.16	62.7	63.10	0.85	0.21	0.42	0.68	10	19.74 ± 2.14	10	28.67 ± 2.89
Type II	straight	E3	0.03	0.16	50.1	47.20	0.87	0.22	0.44	0.70	10	20.03 ± 2.12	10	28.57 ± 5.31
Type II	straight	E4	0.04	0.16	71.7	62.70	0.88	0.22	0.44	0.70	10	18.35 ± 1.61	10	28.05 ± 2.03

Table 4.2. Summary of experimental results. All measurements are at $z = 0.25h_{m.}$

Hydraulis parameters	Experiments							
	E1		E2		E3		E4	
	Main Flow	Resting area	Main Flow	Resting area	Main Flow	Resting area	Main Flow	Resting area
$V_{max.}$ (m.s^{-1})	1.521	0.346	1.543	0.459	1.580	0.390	1.592	0.393
V_{mean} (m.s^{-1})	0.601	0.265	0.771	0.325	0.503	0.205	0.707	0.227
$V_{min.}$ (m.s^{-1})	0.269	0.166	0.415	0.220	0.168	0.130	0.208	0.156
K_{max}. (m^{2}.s^{-2})	0.268	0.027	0.569	0.040	0.335	0.046	0.472	0.053
K_{mean} (m^{2}.s^{-2})	0.078	0.017	0.123	0.024	0.100	0.014	0.160	0.019
$K_{min.}$ (m^{2}.s^{-2})	0.020	0.012	0.052	0.017	0.005	0.004	0.008	0.006
$TI_{max.}$	0.521	0.489	0.650	0.529	0.566	0.502	0.718	0.640
TI_{mean}	0.248	0.246	0.238	0.255	0.364	0.315	0.393	0.371
$TI_{min.}$	0.134	0.110	0.114	0.133	0.156	0.138	0.160	0.108
$-\rho\overline{u'v'}_{max}$ (N.m^{-2})*	13.302	5.131	12.985	8.885	68.038	2.547	78.059	3.431
$-\rho\overline{u'v'}_{mean}$ (N.m^{-2})*	-5.115	-0.725	-12.072	-0.734	22.683	-0.140	51.461	-0.338
$-\rho\overline{u'v'}_{min}$ (N.m^{-2})*	-45.061	-4.144	-75.378	-6.983	-0.478	-13.847	-8.564	-9.395

* Extreme values Reynolds shear stresses are here considered.

Table 4.3. Summary of the results from Spearman rank correlation applied to test the effectsof the mean values of velocity (U_c), turbulent kinetic energy (K_c),turbulence itensity (TI_c) and Reynolds shear stres at XY plane ($-ru'v'_c$) in a cell, on fish transit time within the same cell, or both fish size-classes.

Dependent variable	Independent variables	N		Spearman rank test r		*p*	
		Type I	Type II	Type I	Type II	Type I	Type II
	U_c (m.s-1)	20	20	-0.44	0.01	0.013*	0.95
Transit time	K_c (m^2.s-2)	20	20	-0.60	0.02	<0.001***	0.88
(Fish: 15<TL<25 cm)	Ti_c	20	20	-0.41	0.06	0.022*	0.72
	$\overline{-\rho(u'v')_c}$ (N.m-2)	20	20	-0.47	0.01	<0.001***	0.91
	U_c (m.s-1)	20	20	-0.38	0.33	0.035*	0.07
Transit time	K_c (m2.s-2)	20	20	-0.51	0.36	0.003**	0.04
(Fish:25≤TL<35cm)	Ti_c	20	20	-0.30	0.22	0.102	0.23
	$\overline{-\rho(u'v')_c}$ (N.m-2)	20	20	-0.39	-0.25	0.031	0.17

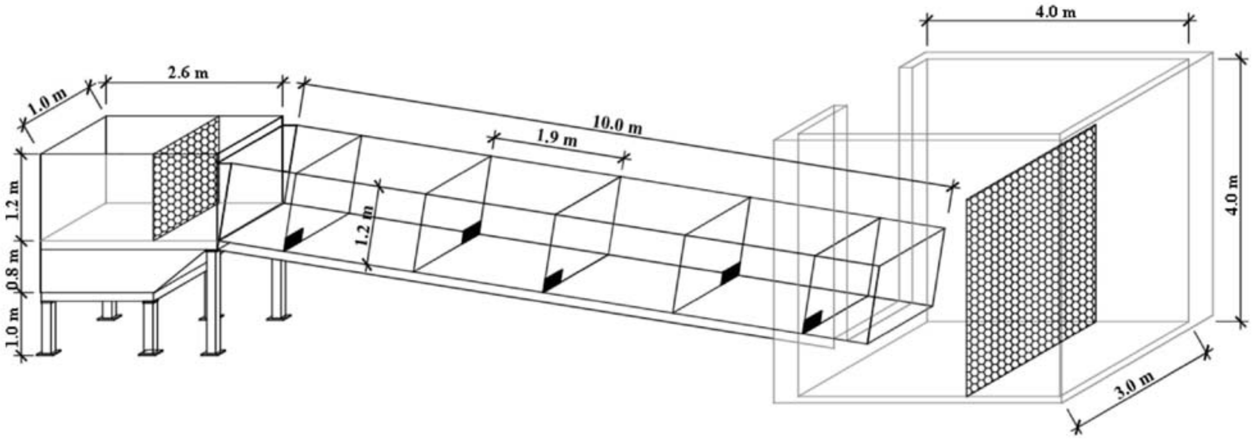
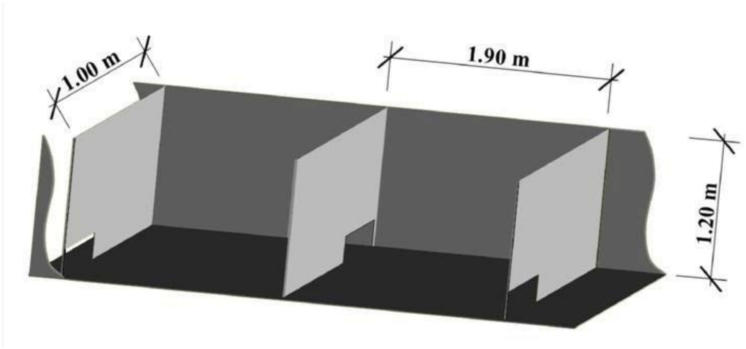
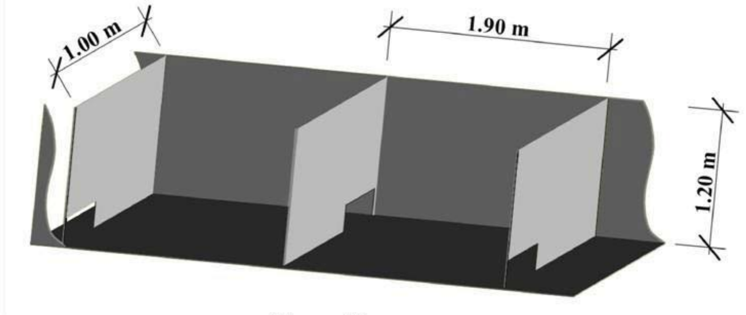


Fig. 4.1. Experimental full scale pool-type fishway at the National Laboratory for Civil Engineering (LNEC).



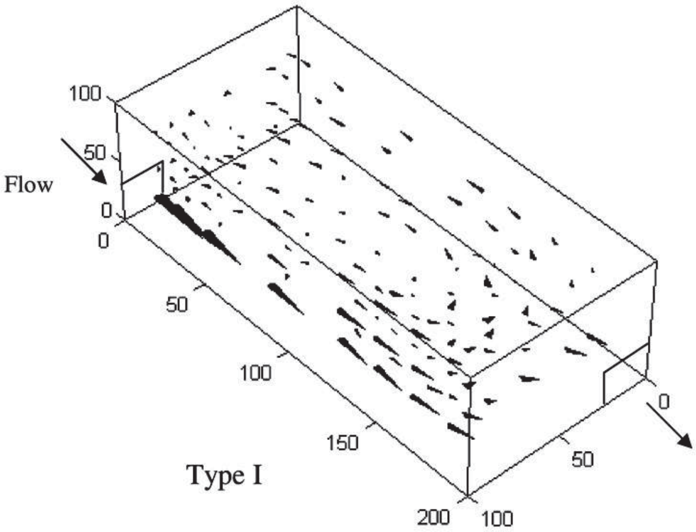
Type I



Type II

Fig. 4.2. Detail of the two types of orifices arrangement tested: (a) offset orifices (Type I); (b) straight orifices (Type II).

(a)



(b)

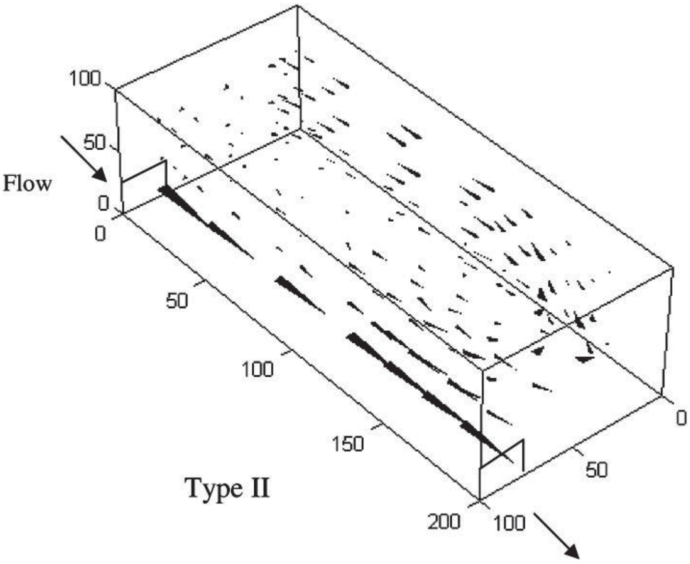


Fig. 4.3. Three-dimensional representation of flow patterns in Type I design (a: $Q = 47.50$ l.s^{-1}, $P_v = 47.80$ W.m^{-3}) and Type II design (b: $Q = 50.10$ l.s^{-1}, $P_v = 47.20$ W.m^{-3}).

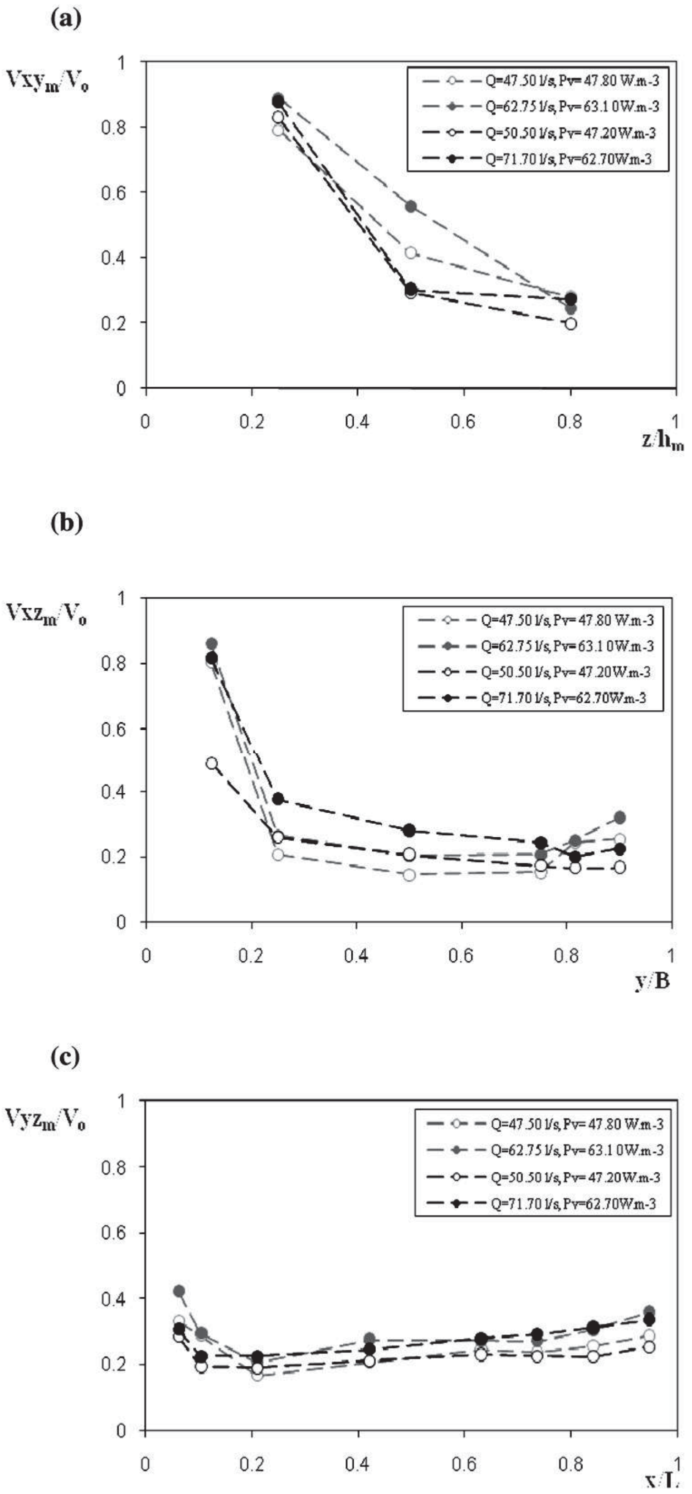


Fig. 4.4. Dimensionless maximum velocities at the experimental tested conditions: (a) horizontal plane (XY); (b) longitudinal plane (XZ) at z = $0.25h_m$; (c) transverse or cross section plane (YZ) at z = $0.25h_m$

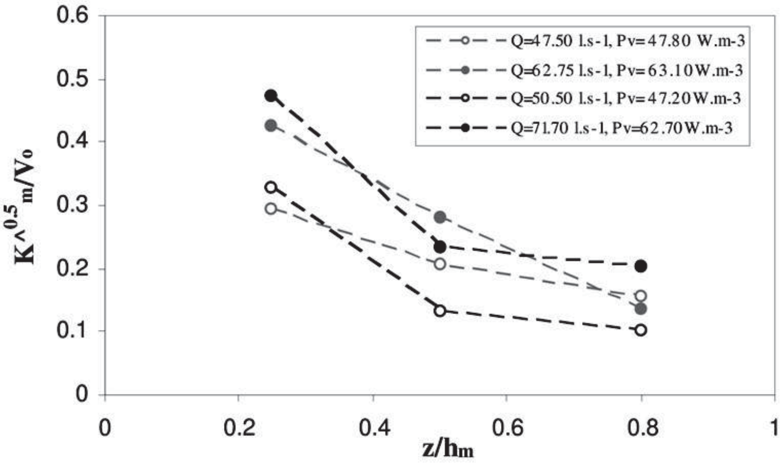


Fig. 4.5. Variation with depth of the dimensionless turbulent kinetic energy $\kappa = K^{0.5}/V_s$ for the experimental tested conditions.

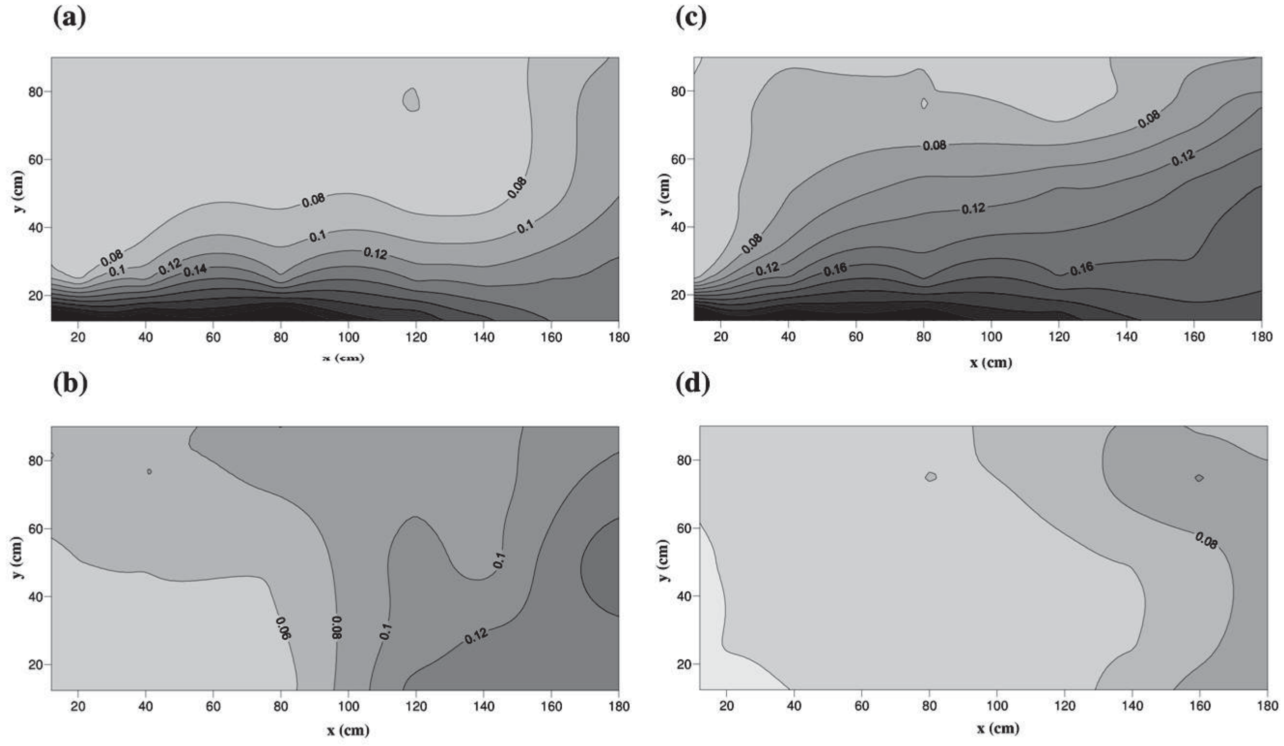


Fig. 4.6. Contours of dimensionless maximum turbulent kinetic energy $\kappa = K^{0.5}{}_m / V_s$ on XY plane for E1: Q = 47.50 $l.s^{-1}$, P_v = 47.80 $W.m^{-3}$ at z = 0.25h_m (a), z = 0.80h_m (b); and for E3: Q = 50.10 $l.s^{-1}$, P_v = 47.20 $W.m^{-3}$ at z = 0.25h_m (c), z = 0.80h_m (d). Flow from the orifice enters at the bottom left of the diagram.

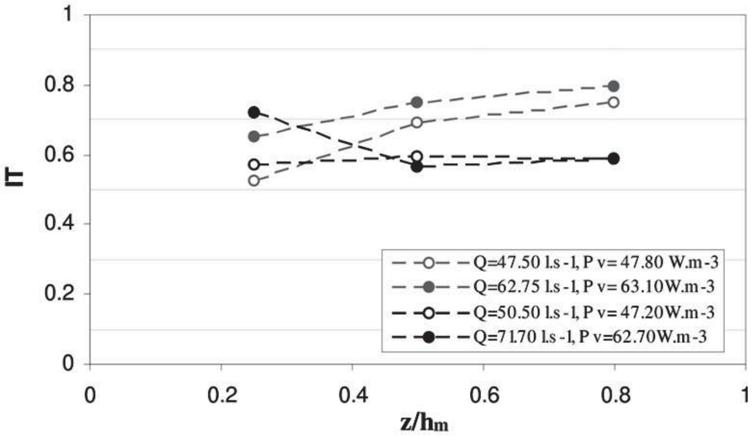


Fig. 4.7. Variation with depth of turbulence intensity (TI) for the experimental tested conditions.

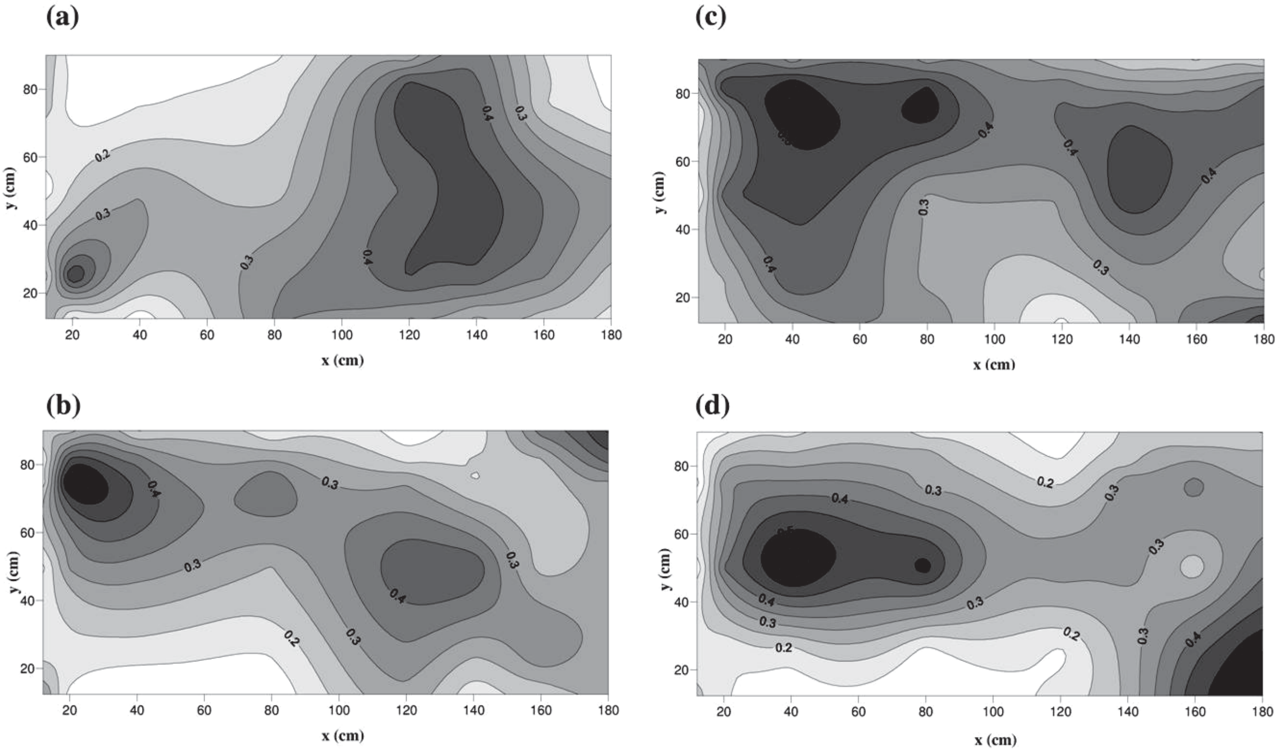


Fig. 4.8. Contours of dimensionless turbulence intensity (TI) on XY plane for E1: Q = 47.50 $l.s^{-1}$, $P_v = 47.80$ $W.m^{-3}$ at $z = 0.20h_m$ (a), $z = 0.80h_m$ (b); and for E3: Q = 50.10 $l.s^{-1}$, $P_v = 47.20$ $W.m^{-3}$ at $z = 0.20h_m$ (c), $z = 0.80h_m$ (d). Flow from the orifice enters at the bottom left of the diagram.

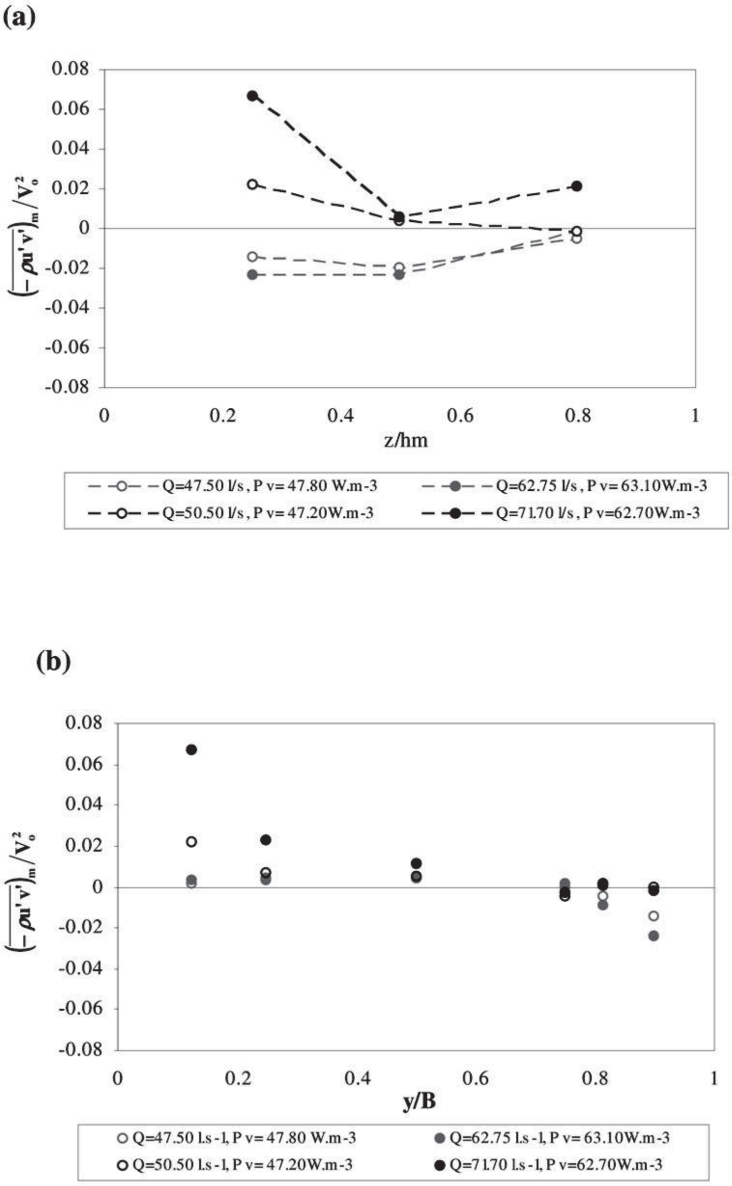


Fig. 4.9. Variation with depth of dimensionless maximum Reynolds shear stress at XY plane $(-\rho\overline{u'v'}_m/V_o^2)$ at the experimental tested conditions.

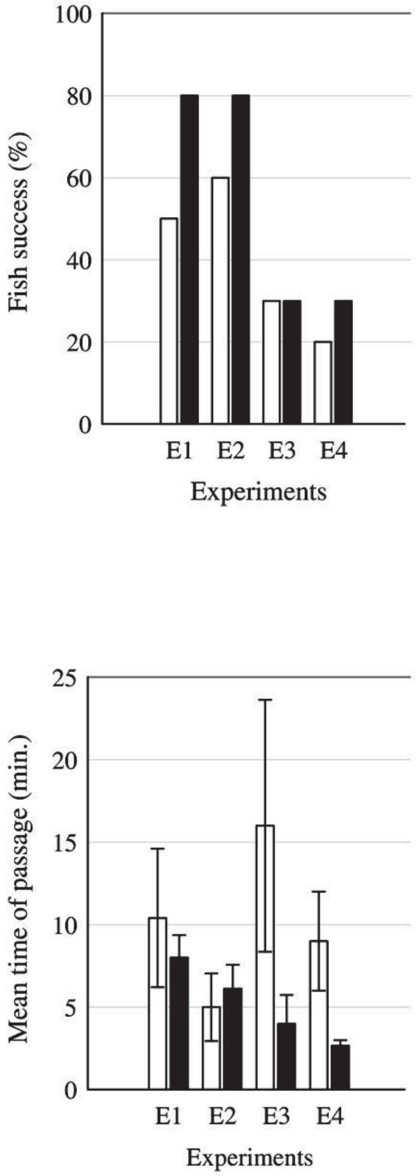


Fig. 4.10. (a) Percentage of fish that successfully negotiated the entire fishway; (b) time taken by fish to negotiate the entire 6 pool fishway (mean ± SE): small adults (15< TL <25 cm) (□) and large adults (25≤ TL < 35 cm) (■).

5. STUDY OF THE EFFICIENCE OF A NEW DESIGN OF POOL-TYPE FISHWAYS FOR THE IBERIAN BARBEL (*LUCIOBARBUS BOCAGEI*, STEINDACHNER 1865) [4]

ABSTRACT

Fishways have revealed to be a good approach to permit unhampered fish's migratory movements. Herein, we studied the adequately of two experimental designs of a pool-type fishways for upstream migration of Iberian barbel in laboratory conditions. The velocity field and turbulence characteristics of flow in pool-type fishway, on offset orifices (Type I) and straight orifices with a deflector bar placed between two consecutive orifices at 0.20L from the upstream orifice with $0.50b_o$ width (Type II), where analysed and related with fish swimming and behavioural capacity. In order to, pointwise measures of velocity were performed at 0.25, 0.50 and $0.80h_m$ by a 3D ADV and the turbulence parameters (Turbulent kinetic energy and Reynolds shear stress) characterized. Overall, a total of 80 Iberian barbel (40: 15<TL<25cm and 40: 25≤TL<35cm) were tested for different flow discharges ($38.50\ l.s^{-1}$ and $62.70\ l.s^{-1}$). Each trial was conducted with two adult fish, one of each size-class. Differences on flow patterns, velocities and turbulence were found for both experimental configurations leading to different fish behaviours. Type I was observed to be more favourable for fish upwards movement, in particularly for large adults, which barely overtake the hydraulic conditions existents in Type II. Small adult showed a higher rheostatic capacity, resulting in higher passage efficiency, in both experimental designs. Hydraulic variables, in particularly turbulent kinetic energy and Reynolds shear stress were found to strongly affect fish behaviour within the fishway, in particularly small adults. This study provides fish passage criteria for an infrequently studied species, the Iberian barbel, and insights to improve fishways suitability for a wider range of species with similar biomechanical features.

KEY WORDS: coarse-fish, deflector bar, submerged orifices, fish size-class, flow pattern, velocity, turbulent kinetic energy, Reynold's shear stress

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[4] Based on paper: Silva AT, Santos JM, Ferreira MT, Pinheiro AN.. Study of the efficiency of a new design of pool-type fishway for the Iberian barbel (*Luciobarbus bocage*i Steindachner 1865).

5.1. INTRODUCTION

From the last decades rivers have been intensively used by man (Arthington and Welcomme, 1995), so that, freshwater systems can be considered as some of the most modified ecosystems in earth, in which a evident rapid decrement of freshwater biodiversity has been occurred (Saunders *et al.*, 2002). River fragmentation by dams and weirs is one of the major causes for the dramatic decline in the range and abundance of freshwater fish (Cowx and Welcomme, 1998; Knaepkens *et al.*, 2007), particularly on those that complete their migrations within the river systems (Nicola *et al.*, 1996; Poulet, 2007), which fish life cycle is greatly disrupting (Cowx and Welcomme, 1998; Knaepkens *et al.*, 2005; Lucas and Baras, 2001; Puertas *et al.*, 2004). In order to minimize such consequences on riverine communities, considerable effort has been devoted to the development of the so-called “fishways” which are of increasing importance for the restoration of passage for migratory fish in rivers (Katopodis *et al.*, 2005; Knaepkens *et al.*, 2005). To develop a good fishways, the interplay between hydraulic and biological variables emerges as the key parameter in this process (Puertas *et al.*, 2004; Rodiguez *et al.*, 2006). Biologically oriented fishway research has focused mostly on anadromous fish species due to their high economical value (Gowans *et al.*, 2003) Research has then been extensively developed focusing anadromous species (Baras *et al.*, 1994; Bunt *et al.* 1999; Gowans *et al.*, 2003; Katopodis 2005; Laine *et al.*, 2002). So, considerably limited information on coarse species, which are frequently the predominant group encountered in Iberian rivers, is available (Baras et al, 1994; Lucas and Frear, 1997; Santos *et al.*, 2005). Considering that most of the coarse fish, such as cyprinids, can travel considerable distances for reproduction, refuge and feeding purposes (Katopodis 2005; Lucas and Frear 1997; Ovidio and Philippart, 2002), a growing interest on research focused on the adaption of fishways for these species (Ead *et al.*, 2004), which greatly differ in their abilities to pass physical and hydraulic obstructions (Knaepkens *et al.*, 2005) when comparing to salmonids has recently brought to light.

In Portugal pool-type fishways are the most common fish pass, in most cases constructed beneath the dimension criteria oriented to salmonids, for which biomechanical skills are rather distinct from the commonest Iberian species. As result, most of these hydraulic devices have shown to be inadequate to the passage of the common fish species in Portuguese rivers. Considering that Portuguese fish fauna ranges from small-size, bottom-dwelling species to large-size long distance migrants, exhibiting a variety of ecological requirements (Santos *et al.*, 2005), the need of developing suitable dimensional criteria of fishways to lowland fish species in Iberian rivers is thus utterly recognized (Stuart and Mallen-Cooper, 1999).

The Iberian barbel *Luciobarbus bocagei* (Steindachner, 1864) is an endemic cyprinid species to the Iberian Peninsula, occurring in almost all of the basins in northern and central Portugal (Geraldes *et al.*, 1993; Lobón-Cerviá *et al.*, 1984; Santos *et al.*, 2005) , which migratory movements are commonly restricted by man-made barriers.

Studies on fish pass use have provided technicians assessment of the numbers and species of fish which successfully negotiate the pass with strong oversights about the effort and behaviour of fish facing the hydraulic conditions existents at the vicinity and within this hydraulic structures (Lupadin, 2005). As rheostatic species, fish's behaviour tends to be orientated to water current. This orientation is an important and widespread behaviour in fish, strongly evident in their upstream migrations and commonly assessed throughout swimming speed (Gregory and Wood, 1999). Fish migratory movements can then be trigger or prevent as result of turbulence's action.

Recent studies focused in the Iberian barbel's migration ecology (Capel and García de Jalón, 1999) have been developed, but yet a small numbers of studies have addressed the Iberian barbel's behavioural response to the hydraulic characteristics existent within a fishway, such as water velocity and turbulence. Therefore, and considering the intrinsic conservation value of this species, it is important to gather data on how the Iberian barbel sense, use and react to velocity and turbulence for a better understanding of the hydraulics effects upon Iberian barbel's swimming performance and energetic, for further improvement of fishways' design (Odeh *et al.*, 2002).

Likewise in a natural river, in laboratory test apparatus flows are turbulent (Vogel, 1981) and therefore turbulence effects on fish can be produced and measured under laboratory settings (Kemp *et al.*, 2006; Odeh *et al.* 2002). Owing to the plethora of interacting factors existent under natural environment, laboratory-simulated conditions, in which the variables of interest can be manipulated, appear as an excellent opportunity to gain generic insights into fish behaviour (Kemp *et al.*, 2006; Tudorache *et a.l,* 2007) and to assess the effects of potential key-variables that should be considered for the successful development of future designs.

This experimental work was thus undertaken in an experimental pool-type prototype, to study the adequacy of two experimental designs of a pool type fishway (offset orifices and straight orifices with a deflector bar) for the Iberian barbel upstream movements. The characteristics of the turbulent flow were studied and analysed in terms influence upon fish behaviour within this type of hydraulic devices.

5.2. MATERIALS AND METHODS

The Fishway

The experiments were conducted in an full-scale experimental pool-type fishway prototype (Figure 5.1) consisting of a rectangular open-channel flume with fiberglass sidewalls externally reinforced by a steel frame, and two concrete tanks located at the upstream and downstream end of the flume; installed at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon. The flume had a total length of 10.0m, 1.0 m of width and 1.20 m of depth. By means of five PVC made cross-walls; each equipped with a submerged orifice of adjustable area; the flume was divided into six pools with 1.90m long per 1.0 m width and 1.20 deep. In order to reduce the likelihood of eddies' occurrence within the experimental area, the bottom of the flume was made smooth, straight and level. Taking into consideration the low swimming capacity of the target species and the range of slopes commonly used in pool-type fishways (Larinier, 2002), the slope of the flume; which was of possible adjustment; was set at 8.5%, have been maintained during all the trials.

Water (soft water) for the fishway was pumped from the laboratory sump into the upstream tank. A total of two pumps were used to supply the required discharge, which could provide a maximum flow capacity of 250 $l.s^{-1}$. To ensure a throughout dechlorination and "maturation" (Copp *et al.*, 1998) of the water used in the experiments, this was maintained within the recirculation system of the laboratory, for at least two weeks previous to the experimental period. The total volumetric discharged required, was measured and controlled by magnetic flow meters located in the supply lines and a flow control valve located at the upstream tank (2.6 m long x 1.0 m wide x 1.2 m high), providing a smooth flow entering in the flume. The water level within the structure was regulated by a slot gate located at the downstream tank (4.0 m long x 3.0 m wide x 4.0 m high). The latter was used as an acclimation chamber for fish, which were kept separately from the flume by a fine-mesh panel (12 m^2). Water temperature, hardness, pH and dissolved oxygen were measured at the beginning and at the end of each trial by using of a multiparametric probe (Hydrolab, Quanta model). In the absence of a temperature control system, water temperature varied as result of the atmospheric temperature variation within the room. The average water temperature during the trials was 18 ± 2ºC, which is within the Iberian rivers temperature range (18 ± 2 ºC) usually found during barbel's migration period.

To unsure uniform lighting and to block sunlight reflection around the structure of the flume a tarpaulin was erected at 4 m above and laterally to the full length of the flume. The structure was illuminated by the lighting system of the laboratory.

Fishway design variants and experiments

A total of two distinct experimental designs of the pool-type fishway were studied experimentally: i) offset orifices (Type I), ii) straight orifices added of a deflector bar (Type II) (Figure 5.2). The selection of the hydraulic arrangements was set in prior experimental studies, designed to study the Iberian barbel behaviour in a pool-type fishway facing different hydraulic conditions. The results showed that fish preferentially use the submerged orifices in their upwards movements (Silva *et al.*, 2009); and that offset orifices arrangement seems to be the most suitable for fish mobility in opposite to straight orifices that originate high velocities fields (Silva *et al.*, unpublished). Also, in the latter configuration, due to the strong unidirectional flow found between two consecutives orifices, the uniformity of flow was not always observed. Attempting to reduce the formers technical hitches, a set of experimental runs was then conducted by placing a deflector bar of variable width ($0.25b_o$ and $0.50b_o$) between two consecutive orifices at 0.20L, 0.40 and 0.60L from the upstream orifice (Table 5.1). A uniform flow (i.e. identical depth at equivalent points with each of the six pools) was thus assumed in the configurations. Fluctuations on head drop between pools were found among the hydraulic conditions tested, ranging between 0.08 and 0.18 m in experiments conducted under lower flow discharges and 0.05 and 0.20 in experiments conducted with higher low discharges. Therefore, based criteria on the head drop (Δh) between two consecutive pool, two configurations were selected for the experimental trials with fish. Configurations tested with bars $0.25b_o$ placed at 0.20L were found to create head drops of 0.16 m, similar to the ones found in Type I, with a maximum flow velocity of 1.77 $m.s^{-1}$, based calculation in formula $V_o=\sqrt{2g\Delta h}$ = 1.77 $m.s^{-1}$, where g is the acceleration due to gravity, 9.80 $m.s^{-2}$ (Larinier, 2002). These were then chosen for tests with fish. Free surface levels, and thus depths, were measured by means of eight rulers fixed to the side-wall of the flume (two at 20 cm increments upstream from the cross-wall; directly in the cross-wall; four at increments of the cross-wall and one at 0.5L).

The fishway was tested for flow discharges (Q) of 38.50 $l.s^{-1}$ and 62.70 $l.s^{-1}$, submerged orifices areas (A_o) of 0.03 m^2 and 0.05 m^2 and two orifice arrangements (straight and offset with deflector bars). Details of the experiments conditions are given in Table 5.2. To provide detailed measurements of the three-dimensional velocity components (x, y, and z) within the flume to map the velocity and turbulence patterns formed inside the pool a NORTEK AS 3D Acoustic Doppler Velocimeter (ADV) was used. Owing to its ability to adequately measure the three-dimensional velocity components (x, y, z) of flowing water (Ead *et al.*, 2004; Guiny *et al.*, 2003; Odeh *et al.*, 2002; Papanicolaou and Maxwell, 2000) by recording the Doppler shift created by changes in wave characteristics caused by the flow of the water relative to a 10 MHz carrier wave (Cotel *et al.*, 2006), either in laboratory or field, the ADV has became recognised as an useful instrument for precise velocity measurements (Cotel *et al.*, 2006; Liu *et al.*, 2006). Attempting to minimize vibration of the ADV probe due to the high velocities existents in the main flow, the probe was set in a rigid beam, mounted in the surface of the flume. Pointwise velocity measurements were obtained at different horizontal planes parallel to the flume bottom, at 25%, 50% and 80% of the pool mean depth (h_m). Because the flow pattern and head drop between pools was found to be similar in most of the pools (Wu et al., 1999), measurements were carried out at the 2nd downstream pool; thus considered representative of the hydraulic conditions existents within the fishway. A predefined grid parallel to the bottom with 48 measurements points distributed according to the velocities fluctuations expected was used as reference (Figure 5.3). Previous studies aiming to establish the sampling period needed for an accurate determination of the mean velocity and turbulence parameters were performed. The ADV was consequently tested for sampling periods ranging between 5 to 350s, have been found that above 30s velocity became almost constant. Taking into consideration that the sampling period required to provide converged statistic of mean and turbulence features is controls by the mean velocity (Liu *et al.*, 2006), a sampling period of 90s was chosen). Overall, 2500 instantaneous measures were recorded for each sample point at a sampling rate up to 25Hz.

Herein, data were used to describe the main factors of hydrodynamic heterogeneity of fish environments, turbulence and current velocity (Lupandin, 2005) within the passage at the horizontal (XY), vertical (XZ) and transversal (YZ) planes, for all the experimental designs tested. Studies focused on fish rheoreaction and fish critical velocity, i.e. the maximum velocity at which a fish can sustain itself in a stream have demonstrated that both decrease with the increase of turbulence (Pavlov *et al.*, 1982). The assessment of the effects of turbulent and respective descriptors, such as turbulent kinetic energy and Reynolds shear stress, upon fish behaviour have been subject of investigation (Pavlov *et al.*, 1994; Puertas *et al.,* 2004; Odeh *et al.*, 2002) and are here addressed attempting to understand their effects upon the Iberian barbel' swimming performance.

A simple indicator of the amount of turbulence is the power dissipation inside the pools per unit volume (Puertas *et al.*, 2004; Rodriguez *et al.*, 2006), which according to the formula used in pool-type fishways (Larinier *et al.*, 1998) is defined as:

$$P_v = \frac{\rho g Q \Delta h}{LBh} \tag{5.1}$$

where ρ is the water density, g the acceleration due to the gravity, Q the flow discharge in the fishway, Δh the water drop between the pools, L and B the length and the width of each pool and h the water depth. The higher the volumetric dissipated power, the more difficult it becomes for fish to travel upstream, therefore herein, experiments were conducted with P_v beneath the upper limit considerer as adequate for cyprinids species (150 W.m^{-3}; Larinier, 2002).

The velocity data, were used to generate calculations of the turbulent kinetic energy (K), which corresponds to the kinetic energy associated to the fluctuating velocity at a given point (Rodi, 1980), and is defined as:

$$K = \frac{1}{2}\left(\overline{u'}^2 + \overline{v'}^2 + \overline{w'}^2\right) \tag{5.2}$$

where, $\overline{u'}$, $\overline{v'}$ and $\overline{w'}$ are respectively root means square values of the fluctuating components of velocity on the system of coordinates *x, y, z*. Greater fluctuations from the mean flow represent greater turbulent kinetic energy, undesirable for fish swimming performance (Liu *et al.*, 2006). However the effects of turbulence on fish vary according to the size of the turbulent fluctuations (turbulence scale). In a river fish are constantly expose to a widely range of turbulence scales, varying from small-scale turbulence associated to tiny eddies which may cause localized damages on fish body surface to larger-scale turbulence, greater than fish size, which can cause the spin of the fish disorientation and loss of equilibrium (Odeh *et al.*, 2002).

To generalize for situations others than the ones tested; K was normalized using the maximum velocity in the orifice (V_o), according to the following equation:

$$\kappa = K^{0.5}{}_m / V_o \tag{5.3}$$

In turbulent flows, parcels of water are moving in different directions with different velocities interacting between them creating shear stress. This latter has been considered as one of the most important hydraulic parameters determining fish behaviour (Odeh *et al*, 2002). Therefore it was here calculated for the horizontal component (XY), by:

$$-\rho\overline{u'v'} \tag{5.4}$$

where ρ is the water density, u' and v' are the fluctuating velocities in X and Y directions, respectively. Previous studies, (Silva *et al.*, unpublished) focused on the tridimensional impact of turbulence and shear stress in the Iberian barbel upstream movements in a pool-type fishway prototype, demonstrated that shear stress acting horizontally affects this specimens, the most. The variations of three-dimensional Reynolds shear stress were therefore assessed at two different layers from the flume bottom: at $0.25h_m$ (close to the bottom) and at $0.80h_m$ (near the surface).

This hydraulic parameter was created dimensionless using the maximum velocity in the orifice (V_o), according to the following equation, for the horizontal plane (XY):

$$\overline{(-u'v')_m}/V_o^2 \tag{5.5}$$

where the subscript *m* refers the maximum value in a transverse profile.

Fish experiments

During April-June 2008 (natural reproductive migration season of the Iberian barbel; Santos *et al.*, 2005), eighty adults Iberian barbels, total length ranging between 15 and 25 cm total length (TL), were caught by means of electrofishing (Electrocatch International, Sarel model WFC7_HV, Wolverhampton, UK) with low voltage (250 v), from the River Sorraia (the largest tributary of the River Tagus_central Portugal). Fish were selected for maturation stage by *in situ* macroscopic observations of gonads development stage and presence of nuptial tubercles (Agostinho *et al.*, 2007). The specimens were brought to the laboratory and according to their size separated into two size-classes: small ($15 < TL < 25$ cm: n= 40, mean 19.35, SD 2.24) and large adults ($25 \leq TL < 35$ cm: n= 40, mean 28.19, SD 3.32), to test for size-related differences in species behaviour. Aiming to recover from handling stress individuals of each size-class (n = 40; 20 individuals per tank) were placed in four tanks, where remained at least one week before experiments started. To ensure good water quality within the tanks, an ELITE aerator systems and mechanical filters were used. Fish were daily fed with pond sticks (Tetra Pond), until 24 h prior to experimentation. In order to simulate natural close conditions favourable to barbel's upstream movements (Santos *et al.*, 2005), all trials were conducted at end afternoon and lasted for 1.5 hours (from 17h00 to 19h30). Each trial consisted of one adult fish of each size-class simultaneously tested for one hydraulic configuration, repeated ten times (Table 5.2), given a total of 40 trials. Fish were randomly removed from the holding tank and placed in the acclimation chamber for approximately 12 hrs to settle. Herein fish were prevented from entering the flume by mesh panel (Figure 5.1). The start of the trials was set; when the discharge in the flume was brought to the desired; by removing the mesh panels to enable fish volitionally ascend the entire flume. In the absence of water control systems, water temperature was shifting (18 ± 2°C) in accordance with the variation of the atmospheric temperature.

Observations and video analysis

Fish behaviour was continuously assessed during all trials, either by direct observation carried out by two operators or by three video cameras, one positioned at 3 m above the water level and two at 2 m of distance of each side of the flume, covering the entire second downstream pool section. In order to aid video analysis a 1.90 long per 1.00 m wide reference grid containing 15 contiguous sequentially numbered cells (each 0.38m length x 0.33 m width) was placed in the pool within the field of the camera view.

Fish in the observation zone were exactly located through the analysis of the video records by using of the IVision Labview software from National Instruments (http://www.ni.com). This procedure was accomplished by one single operator. An individual was considered to A fish was considered to occupy one cell, when more then half of its body length was within a cell's boundaries.

Fish behaviour was analysed at different size-classes counting the number of fish that: i) approached the flume – *Rate of approach to the flume*; ii) enter the flume - *Rate of entrance in the flume per number of approaches*; *iii)* successfully negotiate the fishway - *Fish success*. The time taken by fish to pass the fishway, as well as the time spent by a fish in each cell of the grid (transit time) was counted. The latter was related to the hydraulic parameters previously found for a better understanding of the impact of these upon barbels' swimming performance.

Data analysis

Mostly, fish were found to preferentially remain near the bottom of the fishway, so that analyses were performed using data collected at $z = 0.25h_m$ instead of considering mean values obtained from all the three planes. Herein, the non-parametric Mann-Whitney U-tests were used to test for differences on: *i)* velocity, turbulence kinetic energy and Reynolds shear stress between each of two regions from the three distinct regions created in the two experimental designs (region A, B and C); *ii)* the rate of approach to the flume between experimental designs and between size-classes; *iii*) the rate of entrance in the flume per number of approaches between experimental designs, between size-classes and for each size-class between the experimental designs. Differences on fish success and the respective time taken to pass the fishways for both tested experimental designs were also analyzed by means of the Mann-Whitney U-tests. Also this statistcal test was used to examine for differences on the transit time of each size-class between the two experimental designs and between regions A and B in the first experimental design. Correlations between flow discharge and: the rate of approach to the flume, the rate of entrance in the flume per number of approaches, fish passage efficiency (success) and the respective time to ascend the passage and the transit time of each size-class per experimental design were further analysed using the Spearman rank statistic. Kruskal-Wallis ANOVA test was used to compare the transit times among the three regions created in the second experimental design. The statistical procedure was performed with the Statistic program (version 6.0).

5.3. RESULTS

Overall structure of flow in pools

The different flow patterns in the pools created for the tested configurations are the main factors used to the hydraulic characterization. These, as both, velocity and turbulent fields were found to vary the most in response to the experimental designs tested when comparing to flow discharge. Also, a remarkable variability of these hydraulic parameters was observed at X and Y directions evidence the bidimensional nature of flow, with negligible velocities and turbulence in a vertical component Z. Flow patterns and the respective velocity and turbulence fields' variations for planes parallels to the bottom of the pool for the two different experimental designs (Q= 38.50 $l.s^{-1}$), at z= $0.25h_m$ and z=$0.80h_m$ are plotted in Figure 5.4. Herein, it's clear that velocity and turbulence strongly vary with depth in all the experimental designs.

In Type I, near the bottom, at 0.25 h_m, two clearly defined regions were able to be distinguished (Figure 5.4): region A) a main flow region travels towards the sidewall and the opposite cross-wall until the next orifice characterized by high velocities, occupying approximately 41% of the total area of the pool. creating in the opposite a large recirculation region with reversed flow directions and low velocities (Table 5.3), favourable for fish rest, *"resting-areas"* (region B). Significant differences on velocity between these regions were found in all the experiments (Table 5.4). Near the surface ($z = 0.80\ h_m$), a uniform recirculation flow (counter-clockwise) was observed (Figure 5.4) with lower velocities (Table 5.3). Likewise, in Type II, variation on flow patterns with depth was also clear, as well as three remarkable distinct regions with significant different velocities (Table 4) created near the bottom of the flume (Figure 5.4). Herein, the main flow (region A), characterized by high velocities (Table 5.3), travels directly from the upstream orifice to the deflector bar, shifting direction to the opposite sidewall where it moves all along until the downstream cross-wall keeping its path in direction to the downstream orifice, occupying approximately 40% of the total area of the pool. In between the main flow and the upstream cross-wall, another region (region B) characterized by lower velocities (Table 5.3) and reversal flow pointed to the deflector bar, approached by upstream, was created. Also a third region with the lowest velocities (region C) (Table 5.3) was finding, starting immediately downstream de deflector bar, constrained between 0.42L -0.74L and 0.12B-0.5B. Similar to the first experimental design, herein at the most superficial plane ($z = 0.80\ h_m$) flow pattern varies from the one found near the bottom. Although, differences are fairly evident, predominantly happening in the region B, in which unlikely of what observed near the bottom, flow travels to the upstream corner of the pool (opposite place to the inlet water point).

In Figure 5.5, the ratio between the maximum velocity in each plane (Vxy_m, Vxz_m and Vyz_m) and the maximum velocity in the orifice (V_o) are shown. The vertical variation of velocity within and among each experimental design is undoubtedly evident (Figure 5.5a), particularly in experiments conducted under higher flow discharges. The highest velocities were found in the first experimental design, particularly near the bottom, in the main flow (region A), peaking at $1.54\ m.s^{-1}$ ($0.8V_o$) for the second tested condition (E2). With the proximity to water surface, maximum velocity drastically decreases, clearly evident in experiments conducted under higher flow discharges. Minimum maximum velocity values were then found at $z= 0.80\ h_m$, with values around $0.40\ m.s^{-1}$ ($0.23\ V_o$), occurring in the first tested configuration (E1).

In the vertical plane (XZ), for the first experimental design (Type I), maximum velocities were found at the vicinity of the side-wall adjacent to the upstream orifice, around $1.52\ m.s^{-1}$ ($0.86V_o$) at approximately 0.12L, decreasing towards the opposite side-wall (Figure 5.5b). In Type II, maximum velocities were higher in the middle of the pool, ranging between

0.44 and 0.77 m.s^{-1}, (0.25h$_m$ and 0.44$_{hm}$). In both experimental designs variations in velocities with flow discharge were barely evident.

On a transverse plane (YZ), in both experimental design, maximum velocities slightly varied with the increasing discharge, peaking in the vicinity of both cross-walls (0.74 m.s^{-1}, 0.42 V$_o$) in the first experimental design, contrarily of what observed to the second experimental design, where velocities tend, peaking at 0.74 m.s-^{1} at 0.21L of distance from the upstream cross-wall (Figure 5.5c).

In Figure 5.4, the distribution of the contours lines of dimensionless turbulent kinetic energy (κ) in the pool near the bottom and close to water surface in both experimental designs, are plotted . Attempting to quantify the turbulence kinetic energy and to understand its distribution in the two experimental designs of pool-type fishway, a comparative table is presented (Table 5.5).

The dependency of the turbulence kinetic energy on depth is clearly evident, decreasing to particularly low values in the proximity to water surface. Near the bottom (z = 0.25h$_m$) maximum turbulence ranged between 0.32 m^2.s^{-2} and 0.56m^2.s^{-2} (0.32V$_o$ and 0.42 V$_o$) in Type I, and between 0.54 m^2.s^{-2} and 0.70m^2.s^{-2} (0.41V$_o$ and 0.47 V$_o$) in Type II (Table 5.5). Whilst close to the surface (z = 0.80h$_m$) maximum turbulence ranged between 0.05 m^2.s^{-2} and 0.06m^2.s^{-2} (0.13V$_o$ and 0.14 V$_o$) in Type I, and between 0.04 m^2.s^{-2} and 0.09m^2.s^{-2} (0.11V$_o$ and 0.17 V$_o$) in Type II (Table 5.5). Differences of turbulence with depth were clearly evident in experiments conducted under higher flow discharges. In both experimental designs, turbulence was stronger along the main flow decreasing in region B and C (when applicable), (Table 5.3). Significant differences of turbulence were then found among these regions (Table 5.4).

The variation of dimensionless Reynolds shear stress is shown in Figure 5.4. Herein, it is clear the positive direct response of this hydraulic parameter to the increment of water depth (Table 5.5) and flow discharge. Highest values of shears stress were then found near the bottom, for experiments conducted under higher flow discharges, with a maximum of -51.0 N.m^{-2} (-0.01V$_o$), occurring in the second tested configuration (E2 – Table 5.5). Near the surface, at z = 0.80h$_m$, this tension was particularly lower with maximum values ranging between -8.60N.m^{-2} and -5.53 N.m^{-2} (around 0% of V$_o$) in Type I, and between 6.24 N.m^{-2} and 18.58 N.m^{-2} (around 0% of V$_o$) in Type II (Table 5.5). At z = 0.25h$_{m,}$ the greatest values of this hydraulic parameter, were observed in the main flow, drastically decreasing in region B and C (in Type II), (Table 5.3). Differences on shear stress among regions were found, mostly in the first experimental design (Table 5.4). In Type II, differences of shear stress between region B and C were also evident, in general with no significant expression, except in experiments conducted under a higher flow discharge (Table 5.4). Overall, regardless the experimental design hydraulic differences among regions were found to be stronger in experiments conducted under the highest tested flow discharge (Table 5.4)

Rate of approach to the flum*e*

Barbel approach to the flume simultaneously, exhibiting a behavioural typical from schools. The rate of approach to the flume seemed to have been independent of flow discharge for both size-classes (Spearman rank correlation: small adults, r=0.13, p>0.05; large adults r=-0.04, p>0.05) strongly varying with the experimental design (Mann-Whitney U-test: small adults, Z = 3.59, P < 0.001; large adults, Z = 3.93, P < 0.001) (Figure 5.6). The rate of approaches was then lowest in the second type of experimental design (mean ± SE: Type I, 302.25 ± 0.75; Type II: 220.00 ± 2.56). Differences on size-classes were also observed, but with no significant expression (Mann-Whitney U-test: Z = -0.01, P>0.05). Therefore expressed by a slight variation, small adults approached to the flume, the most.

Rate of entrance in the flume per number of approaches

In all experiments, in both experimental designs, the number of fish entering the flume was low (Type I: 8.15 ± 3.54 %; Type II: 10.52 ± 5.96 %) (Figure 5.7) and similar between both experimental designs (Mann-Whitney U-test: Z = -0.57, P>0.05). No relation on the rate of entrances and flow discharge were found (Spearman rank correlation r=0.43, p>0.05). Small adults evidence a stronger capacity to overtake the adverse hydraulic conditions and enter the flume (10.30 ± 5.53%), when comparing with large fish (8.38 ± 4.33%). However no significant differences on the number of entrances in the flume was found between size-classes (Mann-Whitney U-test: Z =-0.07, P > 0.05). Small fish' capacity to enter the flume was found to varied with the experimental design tested (Mann-Whitney U-test: Z = 2.72, P < 0.01), in opposite to what observed to large fish, for which fish' capacity to enter the flume seemed to be independent of such condition (Mann-Whitney U-test: Z = 0.62, P > 0.05).

Fish success

Passage efficiency was higher in the first experimental design (Figure 5.8a), when comparing with the fish success observed in the second experimental design (Type I: 70.25 ± 10.21%; Type II: 35.00 ± 23.80%). For the same experimental design mean passage was similar between, low (Type I: 70.50 ± 10.61%; Type II: 30.00 ±28.28 %) and high flow discharge (Type I: 70.00 ± 14.14%; Type II: 40.00 ± 28.28 %). No relation on passage efficiency and flow discharge was found (Spearman rank correlation r=0.19, p>0.05). Although size-related differences on rate of success were noted (small adults: 62.00 ± 11.66 %; large adults: 43.25 ± 33.60%), no significant differences were found (Mann-Whitney U-test: Z =0.28, P > 0.05).

The time taken by fish to pass the fishways was higher in the second experimental design (mean ± SD (min): 7.83 ± 6.99) when comparing to time taken by fish in experiments conducted under the first experimental design (mean ± SD (min): 5.47 ± 2.39) (Figure 5.8b). Nevertheless, no significant differences on time taken by fish to ascend the fishway were found between the two experimental design (Mann-Whitney U-test: small adults Z =1.36, P > 0.05; large adults Z =-1.09, P > 0.05). Also for the same experimental design time didn’t vary with flow discharge (mean ± SD (min): Type I,5.38 ± 4.06 m; Type II, 3.75 ± 2.47) and high flow discharge (mean ± SD (min):Type I, 5.56 ± 0.79; Type II, 11.91 ± 8.60). Also, no differences on the time taken by fish to ascend the fishway with flow discharge, were found (Spearman rank correlation: r=0.43 p<0.27). Size-related differences were evident, large have fish were observed to take longer to ascend the fishway (mean ± SD (min): 7.16 ± 7.45), when compared to small-size individuals (mean ± SD (min): 6.15. ± 1.44). Nonetheless no significant differences on the time taken by fish to successfully ascend the pass between size-classes, were found (Mann-Whitney U-test: Z = -0.11, P > 0.05).

Fish behaviour within the flume

Likewise, the results observed in previous studies, focused on Iberian barbel behaviour under different hydraulic configurations in an experimental pool-type fishway (Silva *et al.*, unpublished), fish preferentially remained near the bottom of the flume, with a virtual behaviour to the one observed under natural conditions (Capel and Garcia de Jalón, 1999). Nevertheless, fish were found to explore the water column, just to approach the upstream orifices, avoiding the high velocities of the main flow.

Small adults movements and therefore the respective transit time seemed to be independent of the experimental design (Mann-Whitney U-test:, Z = 1.71, P > 0.05) in opposite, the transit time of large adults was found to vary with the experimental design (Mann-Whitney U-test:, Z = 2.18, P < 0.05). In the first experimental design for both size-classes no relations on the transit time of each and flow discharge were found (Spearman rank correlation: small adults, r=0.23, p>0.05; large adults, r=0.24, p>0.05), contrary, in the second experimental design flow discharge was found to have had a strong negative effect upon fish behaviour, in particularly on large adults (Spearman rank correlation: small fish, r=-0.38, p<0.05; large fish, r=-0.80, p<0.001). Fish behaviour in the first experimental design was strongly affected by the existent hydraulic conditions within the pool, particularly by turbulent kinetic energy and Reynolds shear stress existent in the first experimental design (Table 5.6). Small adult's behaviour was found to be affecting by the former hydraulic parameters, the most (Table 5.6). Due to the deeply differences of the hydraulic parameters among the regions create within pools (region A, B and C; see *Overall structure of flow in pools*). In the first experimental design transit time strongly varied between region A and B (Mann-Whitney U-test: small adults, Z = 4.19, P<0.001; large adults, Z = 2.82, P<0.01). In opposite in Type II, no significant differences on transit time among areas were found for both size-classes (Kruskal-Wallis ANOVA: p>0.05). Due to the smoothest hydraulic conditions encountered in the resting area in the first experimental design fish were observed to mainly remain in this area avoiding the high velocities and turbulence in the main flow (Table 5.3). In type II, fish were also observed to avoid the main flow, remaining in the area immediately below the deflector bar, characterized by low velocities (Table 5.3).

5.4. DISCUSSION

This study appears as one of the few studies evaluating fish pass performance to small bottom dwelling fish species, such as cyprinids. A lack of consideration and understanding of the fish passage requirements of species considered to be of low economic value is the main reason for the low development of multi-species fish passage facilities. One of the major problems in fishways is that optimal parameters depend on the interplay between hydraulic and biological variables (Rodriguez *et al*., 2006). Herein, an understanding of the existing flow patterns, velocities and turbulence in two different hydraulic configurations in an experimental pool-type fishway prototype was analyzed and studied in terms of suitability to Iberian barbel, of two different size-classes, upstream movements. As many others laboratory studies (Guiny *et al.,* 2003) this work proved to be a powerful tool to knowledge improvement in the design of fishway, providing important information about the Iberian barbel's hydraulic requirements that will aid the development of appropriate fish passage criteria for this species.

Clearly distinct in terms of hydraulics, both experimental designs tested, seemed like to permit barbel upstream movements. Although, the rate of approach to the flume and the rate of entrance in the flume per number of approaches have been higher in the second experimental design, offset orifices configuration was found to be more favourable to barbel's passage as shown by the respective higher rate of success (70.25 ± 10.21%) in detriment to the success obtained in the second experimental design (35.00 ± 23.80%). Even though the concept of fishway efficiency (defined as the proportion of fish present at the acclimation chamber that successfully negotiated the fishway) has not been formally defined in terms of minimum standards (Larinier, 1998), it is generally considered that efficiencies should be 90-100% for diadromous species, whereas for potamodromous cyprinid species, such as the Iberian barbel, the successful passage of a certain number of individuals, in relation to the population in place may be sufficient to ensure the longitudinal connectivity of river systems and avoid fragmentation of the populations (Porcher and Travade, 2002). Added the highest required times from fish to ascend the fishway when facing the hydraulic conditions existent in second experimental design, it is therefore believed that the first design of the fishway was well designed, as shown by a fairly "reasonable" proportion, of Iberian barbel that successfully negotiated the device. Such results appear as consequence of the hydraulic difference clearly evident between the two experimental designs, expressed by different flow patterns, velocities and turbulence.

In all the experiments fish preferentially remained near the bottom of the flume, characteristic feature of under natural conditions, what can be seen as a good indicator of the verisimilitude between fish behaviour under experimental conditions and under the natural environmental, sustaining the idea that hydraulic effects on fish can be produced and measured under laboratory settings (Kemp *et al.*, 2006; Odeh *et al.* 2002).

In the natural habitat, fish are usually confronted with the need to get to compromises among many interacting physical and biotic factors (Slavik *et al.*, 2009; Cotel *et al.*, 2006) attempting to achieve stability in a specific location. Although it is function of perturbation magnitude, stability which implies the ability to control posture and location in water column, is also dependent on the momentum (Cotel *et al.*, 2006) and therefore on the hydraulic parameter's fluctuations, as velocity a turbulence (Bunt, 2001; Odeh *et al.*, 2002; Lupandin, 2005). Therefore it is comprehensible that fish response differently to the hydraulic conditions existent in the two experimental designs. Though, the lowest velocities and Reynolds shear stress found in the second experimental design, the flow pattern created and the respective turbulent kinetic energy seemed to strongly disturb fish capacity to achieve stability, resulting in absence of differences on the transit time among the three distinct hydraulic created. Although the area occupied by both main flow created the two experimental design were similar, fish were found to face strong difficulties to overtake the velocities and turbulence of the main flow, in the second experimental design until reach the so-called "*resting areas*". In opposite the prominent lateral position of the main flow in the first experimental design seemed like to be more favourable to fish reaching the resting areas within a pool and therefore rest and recover from the energy spending to pass the cross-wall. It is known that fish tend to use the maximum critical swimming speed when crossing the cross-walls (Larinier, 2002; Odeh *et al.*, 2002; Mateus *et al.*, 2008) followed by a decrease of swimming velocity, leading to an intern equilibrium of energy which aid fish to negotiate the hydraulic conditions with a minimum energy expenditure (Pavlov *et al.*, 2000). Nevertheless, due to both the high velocities in the primary flow, its prominent location occupying the central area of the pool and the additional energy expenditure required for fish to balance control in such adverse condition, both, fish swimming capacity and the likelihood to achieve an equilibrium point decreased, leading to the observed fish disorientation and constant displacement even in areas with low velocity.

Fish capacity to face adverse hydraulic conditions in a fish ladder, strongly dependents on fish size (Slavik et al, 2009; Silva et al, unpublished). In the first experimental design no differences were noted between both size-classes, however in the second experimental design small fish showed a higher capacity to overtake the hydraulic conditions and successfully pass the fishway. Herein the higher rheostatic capacity of small barbels found in previous studied developed under natural conditions (Capel and Garcia de Jalón, 1999) is evident.

The effects of turbulence kinetic energy (K) on fish behaviour were extremely pronounced, clearly evident through the negative correlations found between this hydraulic parameter and transit time as well as by the apparent disorientation of fish whilst attempting to swim in turbulent flow. It is of general understanding that the impact of turbulence on fish's swimming capacity strongly varies according to the shape and size of turbulence vortex (turbulence scale) exercised on fish body (Lupandin, 2005; Odeh *et al*, 2002). Therefore, the observed fish orientation at all angles, including inverted in the second experimental design can be explain as the result of the impact of the vortex structure of turbulence on fish body, which disturbs fish balance (Lupandin, 2005). Adding the limited swimming capacity of this species (Doadrio, 2001) and the high energy expenditure required by fish to maintain its balance in turbulent flow condition (Pavlov *et al.*, 2000), all these factors can be recognized as the main reasons to the prominent occurrence of fish in areas with low velocities and turbulence. The use of low turbulent kinetic energy locations by Iberian barbel as resting areas before subsequent efforts to traverse areas of higher velocity and turbulence (i.e. near or through orifices), highlights the importance of this parameter, that should be taken into account when designing fishways for this species.

Likewise K and TI, Reynolds Shear Stress is a turbulence parameter with great impact on fish behaviour. As shown by the high correlations between fish transit time and Reynolds shear stress on the XY plane ($\overline{-\rho u'v'_c}$), found in the first experimental design. This result, as shown in others studies (Odeh *et al.*, 2002; Silva *et al.*, 2009 unpublished,), points towards to the importance of Reynolds shear stress as key-parameter determinant of fish' movements within a pool-type fishways. The effects of this parameter on fish vary according to the intensity of which it is applied as well as with the target species, whose sensitivity to strain is different. It is known that within confined man-made structures such as submerged orifices of pool-type fishways high and potentially undesirable values of shear stress can occur (Cada *et al.*, 2006). High Reynolds Shear Stress might cause injuries or even mortalities (Nietzel *et al.*, 2000), which typically occur at much higher levels ($\geq$ 700 N.m^{-2}) (Cada *et al.*, 1999). The absence of any type of injuries in the tested fish indicates that shear stress existent within the experimental conditions were suitable for this species swimming capacity, dovetailing in the range of the estimates values in a medium-size stream ($\leq$ 30 N.m^{-2}). As with the other hydraulic parameters, the effects of Reynolds shear stress were most prominent in the smaller-size individuals, as shown by the highest correlations with fish transit time, highlighting the use of different size-classes upon studying the effects of hydraulics on fish.

The finding results suggest that a pool-type fishway seems to be a suitable facility to free instream movement of Iberian barbel. The strong orientation of fish movements by the hydraulic conditions existent within the fishway, in particularly by turbulent kinetic energy and Reynolds shear stress, reveals that especially noteworthy should be taken to these hydraulics parameters whilst the development of a fishway design. The modification of internal flow characteristics in the pools by placement of submerged structures to examine the extent to which turbulence, particularly the horizontal Reynolds shear stress component can be reduced, and thus facilitate passage of small individuals, should be considered on future fish passage studies. The results are believed to provide useful insights about Iberian barbel biological and hydraulic requirements to developing realistic fish passage criteria for this species. Continued efforts must be directed at developing greater understanding of how river infrastructure can impede the movements of migratory cycles of species others than salmonids.

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Table 5.1. Characterization of the previous tested hydraulic configurations.

Experiments	A_o (m^2)	% L	d (m)	% b_o	b_o (m)	Q ($l.s^{-1}$)	P_v ($W.m^3$)	h_m (m)	25% h_m (m)	50% h_m (m)	80% h_m (m)
1	0.03	0.20	0,38	0.25	0.450	38.5	37.0	0.88	0.22	0.44	0.70
2		0.20	0,38	0.50	0.900						
3		0.40	0,76	0.25	0.450						
4		0.40	0,76	0.50	0.900						
5		0.60	1,14	0.25	0.450						
6		0.60	1,14	0.50	0.900						
7	0.05	0.20	0,38	0.25	0.580	62.7	63.1	0.84	0.21	0.42	0.67
8		0.20	0,38	0.50	0.115						
9		0.40	0,76	0.25	0.580						
10		0.40	0,76	0.50	0.115						
11		0.60	1,14	0.25	0.580						
12		0.60	1,14	0.50	0.115						

Table 5.2. Details of the hydraulic conditions of the two experimental tested designs: submerged orifices area (A_o), head drop between pools (Δh), volumetric power dissipation (P_v), pool mean water depth at 25, 50 and 80%. Number (N) and fish size of individuals used in the experiments.

Design	Experiments	Variables											
		A_o (m^2)	Δh (m)	Q ($l.s^{-1}$)	P_v ($W.m^{-3}$)	h_m (m)	25% h_m (m)	50% h_m (m)	80% h_m (m)	Small adults : 15<TL <25cm		Large adults: 25≤ TL <35cm	
										N	Mean ± SD (cm)	N	Mean ± SD (cm)
Type I	E1	0.03	0.16	38.5	37.0	0.79	0.20	0.40	0.63	10	19.07 ± 1.76	10	28.87 ± 2.59
	E2	0.05	0.16	62.7	63.1	0.85	0.21	0.42	0.68	10	19.74 ± 2.14	10	28.67 ± 2.89
Type II	E3	0.03	0.16	38.5	37.0	0.88	0.23	0.45	0.72	10	20.15 ± 2.49	10	30.61± 2.46
	E4	0.05	0.16	62.7	63.1	0.84	0.22	0.44	0.70	10	20.18 ± 4.53	10	30.98 ± 2.40

Table 5.3. Hydraulic characterization of regions A, B and C for each experimental design. Measures were taken at $z=0.25h_m$.

Hydraulis parameters	Experiments									
	Type I				Type II					
	E1		E2		E3			E4		
	Main Flow (Region A)	Resting area (Region B)	Main Flow (Region A)	Resting area (Region B)	Main Flow (region A)	Resting area (Region B)	Resting area (Region C)	Main Flow (region A)	Resting area (Region B)	Resting área (Region C)
$V_{max.}$ ($m.s^{-1}$)	1.042	0.289	1.543	0.459	0.994	0.215	0.246	1.245	0.854	0.297
V_{mean} ($m.s^{-1}$)	0.452	0.224	0.771	0.325	0.358	0.143	0.160	0.487	0.222	0.194
$V_{min.}$ ($m.s^{-1}$)	0.191	0.139	0.415	0.220	0.124	0.086	0.093	0.150	0.090	0.085
K_{max}. ($m^2.s^{-2}$)	0.324	0.027	0.569	0.040	0.704	0.051	0.095	0.540	0.372	0.036
K_{mean} ($m^2.s^{-2}$)	0.059	0.011	0.123	0.024	0.079	0.012	0.024	0.097	0.058	0.016
$K_{min.}$ ($m^2.s^{-2}$)	0.006	0.007	0.052	0.017	0.010	0.005	0.005	0.021	0.008	0.007
$-\rho\overline{u'v'}_{max}$ ($N.m^{-2}$) *	7.665	4.904	12.985	8.885	47.731	5.924	7.109	24.743	3.162	6.271
$-\rho\overline{u'v'}_{mean}$ ($N.m^{-2}$) *	-4.519	-0.129	-12.072	-0.734	0.415	-0.465	-0.251	-3.314	-3.916	0.625
$-\rho\overline{u'v'}_{min}$ ($N.m^{-2}$) *	-43.907	-1.991	-51.378	-6.983	-41.377	-3.545	-5.861	-45.080	-31.300	-5.355

* Extreme values Reynolds shear stress are here considered

Table 5.4. Mann-Whitney U-test coefficients obtained when testing for differences on the hydraulic variables (velocity, turbulent kinetic energy and Reynolds shear stress) among the three created regions (A, B, C) in Type I and Type II.

Design	Experiments	Regions	Hydraulic variables		
			v ($m.s^{-1}$)	K ($m^2.s^{-2}$)	$-\rho u'v'(N.m^{-3})$
Type I	E1	A-B	4.37***	4.66***	-2.49**
	E2	A-B	5.70***	5.26***	-3.13***
Type II	E3	A-B	4.48***	3.24***	0.33^{ns}
		A-C	3.81***	2.47**	-0.08^{ns}
		B-C	-0.84^{ns}	-0.53^{ns}	-0.21^{ns}
	E4	A-B	3.38***	1.47^{ns}	-0.49^{ns}
		A-C	3.58***	3.52***	-2.08*
		B-C	-0.70^{ns}	1.41^{ns}	-2.32*

* Significant in P<0.05; ** significant in P < 0.01; *** significant in P<0.001; ^{ns} no significant

Table 5.5. Summary of the variation of maximum turbulence parameters (Turbulent kinetic energy and Reynolds shear stress) with depth for both experimental tested designs.

Hydraulis parameters	Experiments					
			Type I		TypeII	
			E1	E2	E3	E4
K_{max}. ($m^2.s^{-2}$)	z (%hm)	25	0.324	0.568	0.700	0.540
		50	0.065	0.386	0.280	0.210
		80	0.049	0.058	0.040	0.090
κ	z (%hm)	25	0.322	0.426	0.473	0.415
		50	0.144	0.351	0.299	0.259
		80	0.125	0.136	0.113	0.169
$-\rho\overline{u'v'}_{max}$(N.$m^{-2}$)	z (%hm)	25	-43.900	-51.000	47.730	-45.080
		50	-17.410	-20.320	7.910	61.280
		80	-8.600	-5.539	6.240	18.580
$-\rho\overline{u'v'}_{max}/V_o$	z (%hm)	25	-0.014	-0.016	0.015	-0.014
		50	-0.006	-0.006	0.003	0.020
		80	-0.003	-0.002	0.002	0.006

Parameters analysed (velocity, turbulent kinetic energy and Reynolds shear stress (xy plane). *P<0.05; **P<0.01; ***P<0.001.

Table 5.6. Spearman rank test results obtained when correlating fish's transit time in Type I and Type II with the different hydraulic variables (velocity, turbulent kinetic energy and Reynolds shear stress).

Design	Fish size-class	Dependent variable	N	Speraman rank r	P-value
Type I	15<TL<25 cm	v (m.s-1)	20	-0.39	0.030*
		K (m2.s-2)	20	-0.37	0.030*
		$-\rho u'v'$(N.m-2)	20	0.18	0.330
		$\lvert -\rho u'v' \rvert$ (N.m-2)	20	-0.5	0.003**
	25≤TL<35cm	v ($m.s^{-1}$)	20	-0.45	0.010*
		K ($m^2.s^{-2}$)	20	-0.46	0.009**
		$-\rho u'v'$($N.m^{-2}$)	20	0.2	0.200
		$\lvert -\rho u'v' \rvert$ ($N.m^{-2}$)	20	-0.27	0.130
Type II	15<TL<25 cm	v ($m.s^{-1}$)	20	-0.11	0.054
		K ($m^2.s^{-2}$)	20	0.11	0.550
		$-\rho u'v'$($N.m^{-2}$)	20	0.53	0.002**
		$\lvert -\rho u'v' \rvert$ ($N.m^{-2}$)	20	0.03	0.840
	25≤TL<35cm	v ($m.s^{-1}$)	20	-0.13	0.500
		K ($m^2.s^{-2}$)	20	0.09	0.650
		$-\rho u'v'$($N.m^{-2}$)	20	0.45	0.010*
		$\lvert -\rho u'v' \rvert$ ($N.m^{-2}$)	20	-0.08	0.660

Parameters analysed (velocity, turbulent kinetic energy and Reynolds shear stress (XYplane). *P<0.05; **P<0.01; ***P<0.001.

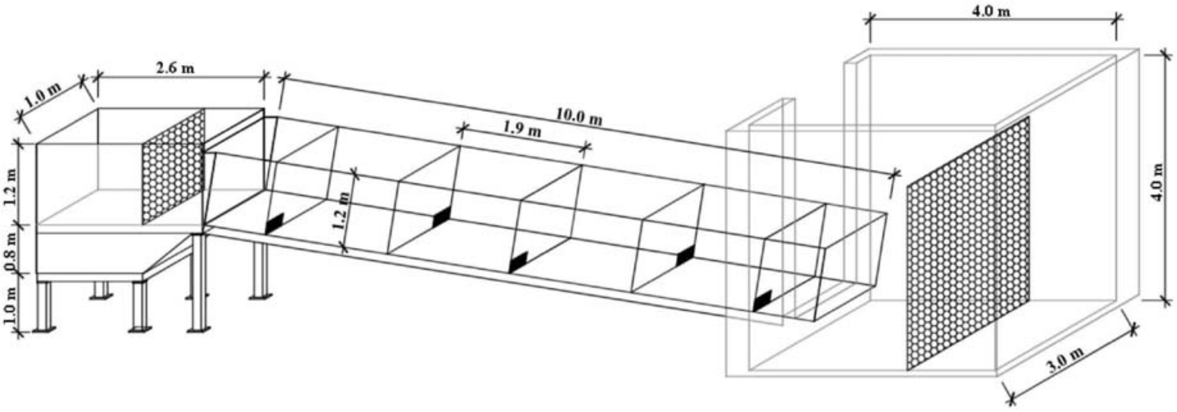
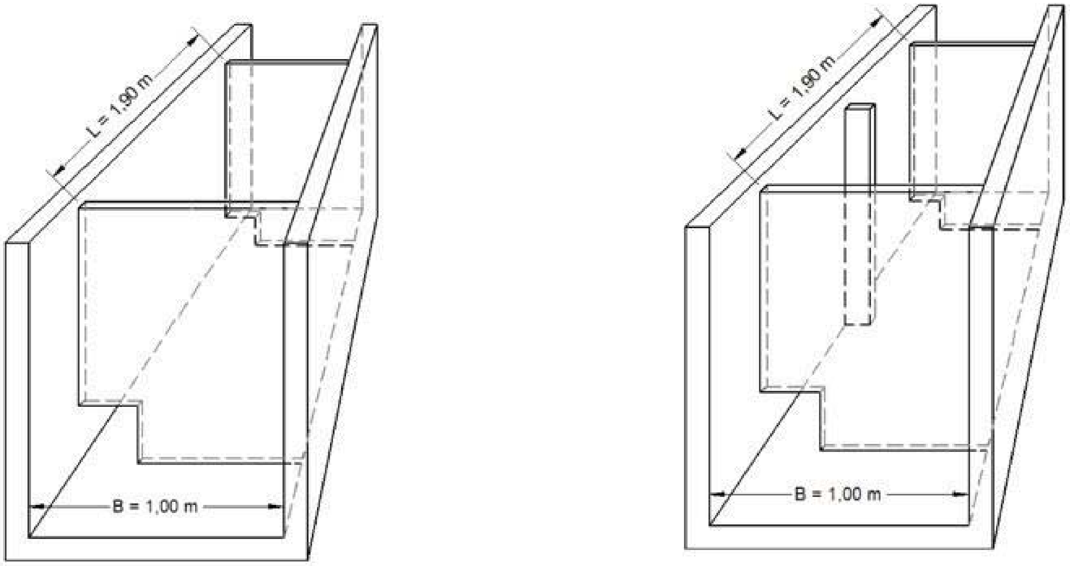


Fig. 5.1. Experimental full scale pool-type fishway installed at the National Laboratory for Civil Engineering (LNEC).



Type I

Type II

Fig. 5.2. The two experimental designs evaluated in the present study: (a) offset orifices (Type I); (b) straight orifices with a deflector bar (Type II).

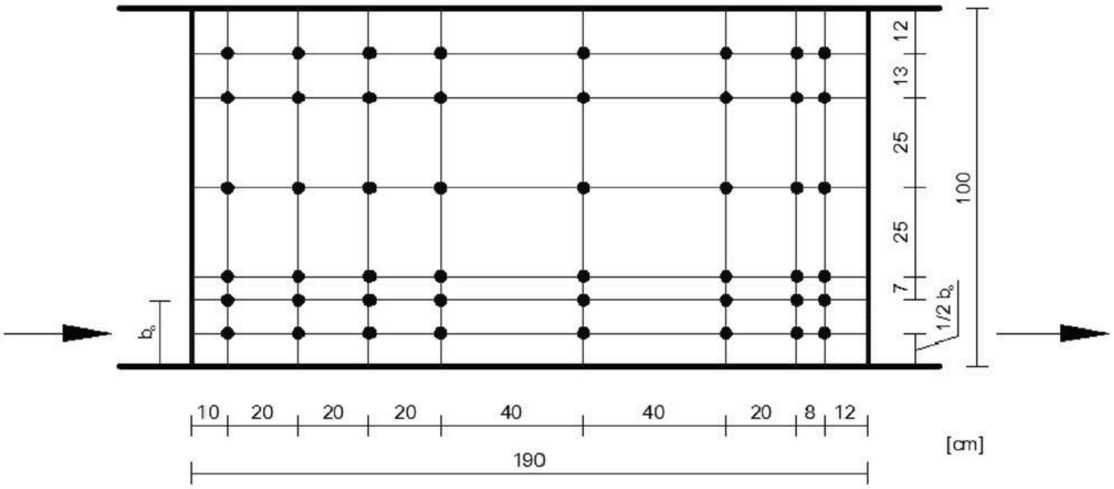


Fig. 5.3. Grid used for velocity measurements in planes parallels to the bottom of the flume.

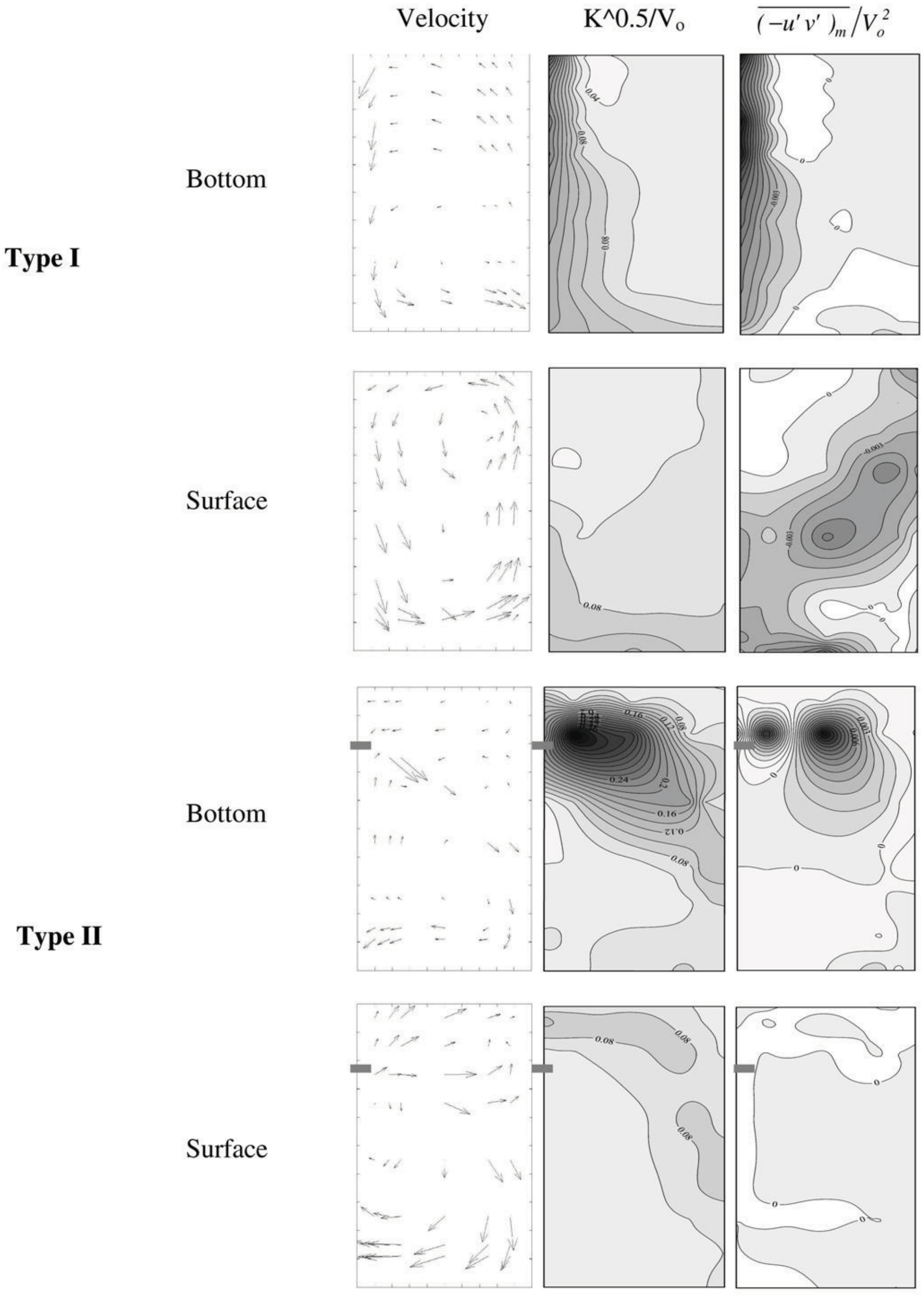


Fig. 5.4. Representation of the fields' variation of velocity, dimensionless turbulent kinetic energy and dimensionless Reynolds shear stress in the horizontal plane (XY) parallel to the bottom ($z=0.25h_m$) and to the surface ($z=0.80h_m$) for both experimental designs, Q= 38.50 $l.s^{-1}$.

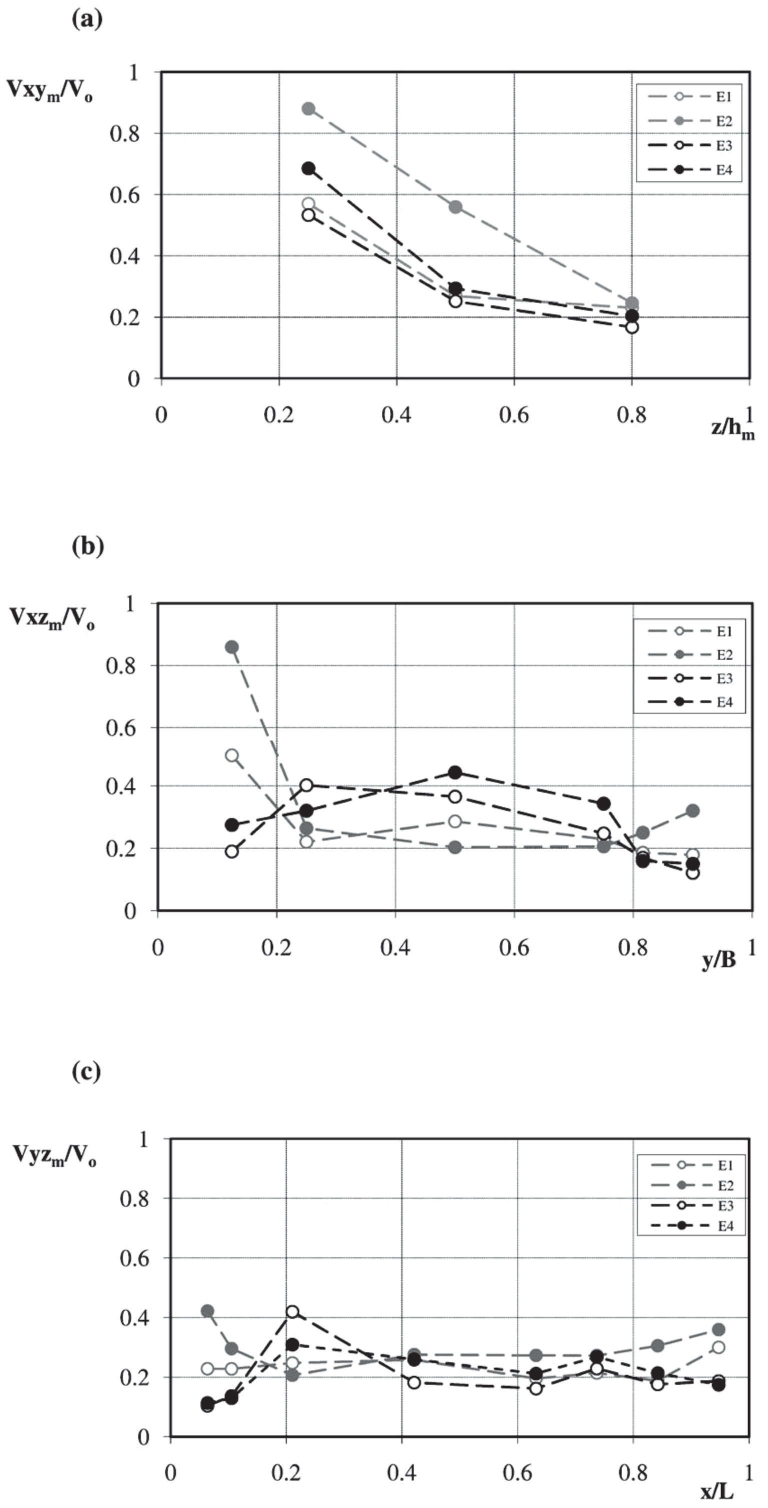


Fig. 5.5. Dimensionless maximum velocities at various tested discharges on different planes: (a) horizontal plane (XY); (b) vertical plane (XZ); (c) transversal plane (YZ).

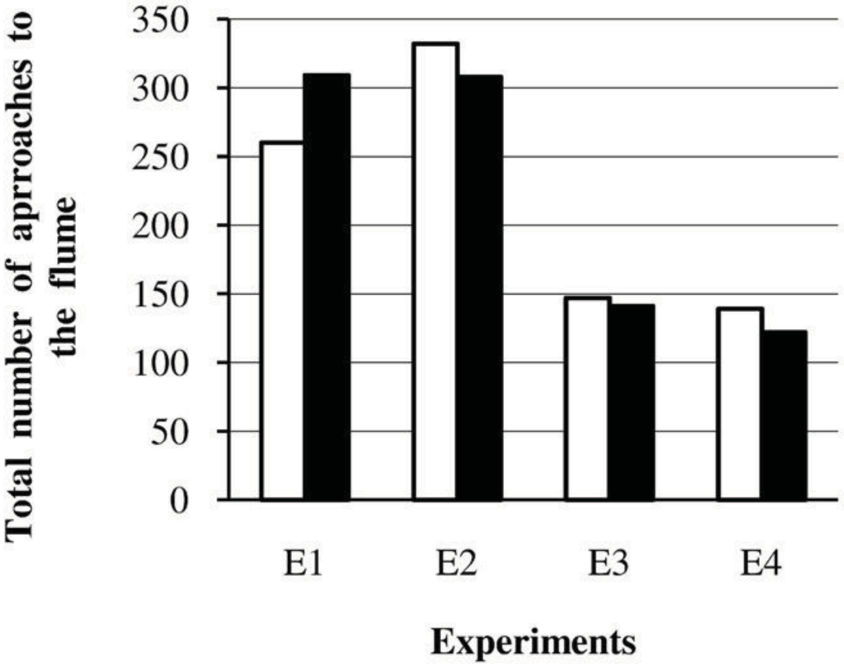


Fig. 5.6. Total number of approaches to the flume by small adults (15< TL <25 cm) (□) and large adults (25≤ TL < 35 cm) (■), in all the experiments.

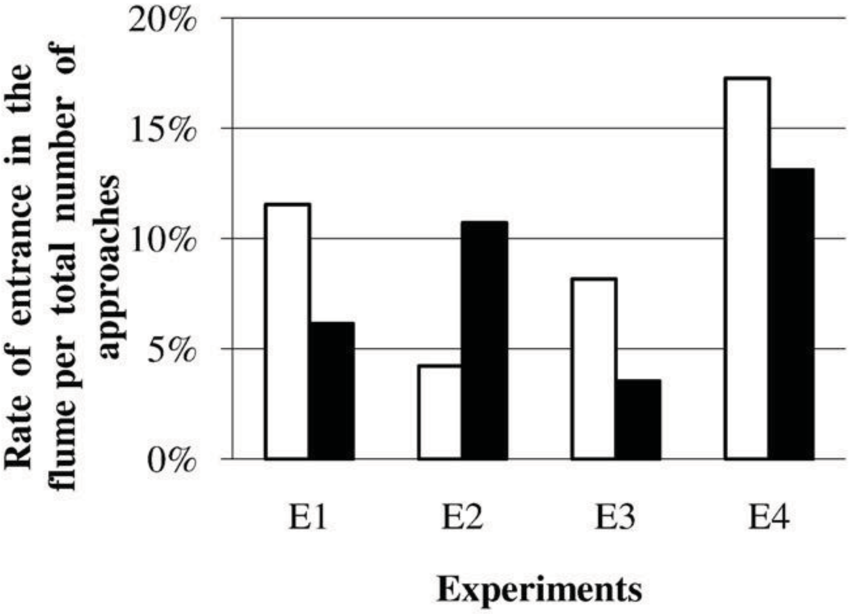


Fig. 5.7. Rate of entrance in the flume per total number of approaches by small adults (15< TL <25 cm) (□) and large adults (25≤ TL < 35 cm) (■), in all the experiments.

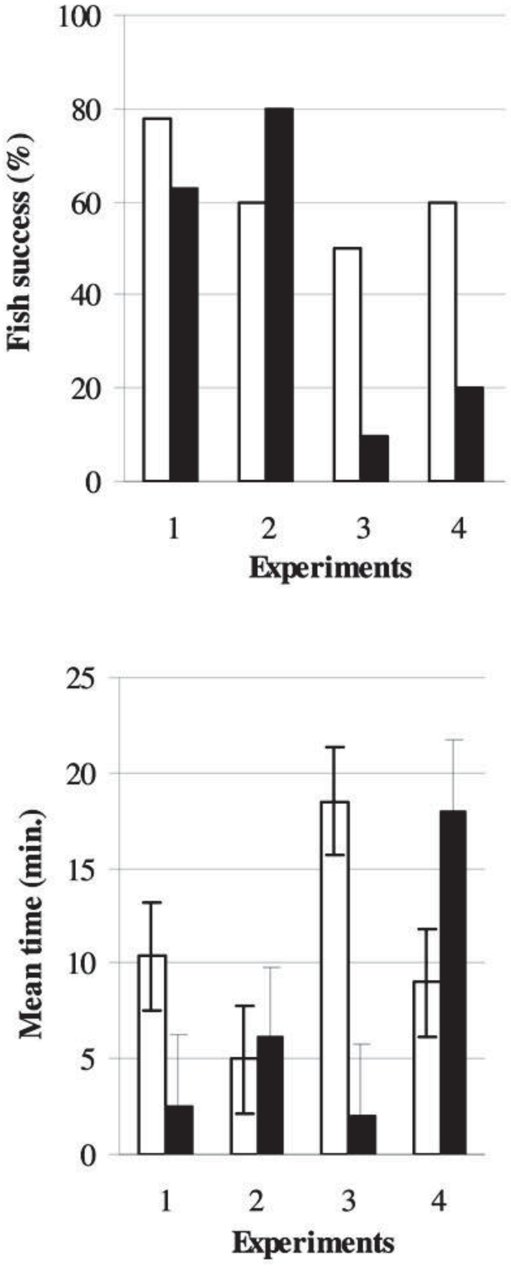


Fig. 5.8. (a) Percentage of fish that successfully negotiated the entire fishway in both experimental designs; (b) time taken by fish to pass the fishway (mean ± SE): small adults (15< TL <25 cm) (□) and large adults (25≤ TL < 35 cm) (■).

6. SÍNTESE E CONCLUSÕES

Neste trabalho avaliou-se, a nível experimental, a eficiência de várias configurações de uma passagem para peixes por bacias sucessivas à passagem para montante do barbo Ibérico. Pretendeu-se aprofundar os conhecimentos sobre a interacção entre os parâmetros hidráulicos e as especificações biológicas desta espécie, visando encontrar indicadores passíveis de utilização como crtitérios de optimização à concepção deste tipo de estruturas hidráulicas para esta e outras espécies com semelhantes características biomecânicas. A avaliação das características do escoamento turbulento, em conjunto com a avaliação qualitativa do comportamento dos espécimes durante a sua passagem pelo referido dispositivo de passagens para peixes, posssibilitou deste modo atingir o objectivo deste trabalho.

Seguidamente apresenta-se uma súmula das principais conclusões obtidas em cada um dos trabalhos e algumas propostas de possíveis estudos a desenvolver neste âmbito.

6.1. SELECÇÃO DO BARBO IBÉRICO *BARBUS BOCAGEI* (STEINDACHNER, 1864) POR ORIFÍCIOS E DESCARREGADORES DE SUPERFÍCIES SOB DIFFERENTES CONFIGURAÇÕES HIDRÁULICAS NUM PROTÓTIPO EXPERIMENTAL DE UMA PASSAGEM PARA PEIXES POR BACIAS SUCESSIVAS

O estudo da utilização preferencial de orifícios de fundo ou descarregadores de superfícies pelo barbo Ibérico na sua movimentaçãopara montante numa passagem para peixes por bacias sucessivas foi analisado.

As características hidráulicas inerentes às configurações testadas, demonstraram estar bem estruturadas em termos hidráulicos, existindo uma repartição equalitativa entre a velocidadede do escoamento pelos dois tipos de passagem (orifício de fundo e descarregador de superfície). Sendo esta relação de extrema importância para o despiste de eventuais factores tendenciosos à selecção do tipo depassagem. Os orificios de fundo demonstraram ser mais eficientes à passagem dos espécimes, em concordancia com outros estudos. Guiny *et al.* (2003), estudou a preferência de utilização do mesmo tipo de formas de passagem, para duas espécies salmonicolas (*Salmo trutta*, L. e *Salmo salar* L.) tendo verificado que ambas utilizaram preferencialmente os orifícios de fundo para as suas delocação. Considerando que as espécies salmonicolas são caracterizadas por uma boa capacidade de salto e natação, bastante superior à dos ciprinideos, verifica-se que tendencialmente as espécies durante a sua movimentação para montante procuram minimizar o gasto energético inerente a este processo (Hinch e Rand, 2000). O tipo de escoamento na passagem foi igualmente observado como factor primordial a este processo.O maior número de passagens e a utilização equirepartida pelos dois tipos de formas de passagem aquando condições de “afogamento” do descarregador de superficie “Streaming flow”, demontram que este é favorável à passagem de um maior numero de indivíduos e diversidade de espécies piscícolas. A fraca capacidade de salto característica das espécies potamodomas (Doadrio, 2001), geralmente factor limitante à passagem para montante destas espécies aquando a transposição de dispositivos de passagem, poderá então ser contornada pela implantação de regimes de escoamento que permitam o afogamento dos descarregadores de superfície possibilitando a que os espécimes nadem por cima da soleira do descarregador aquando das suas movimentações para montante.

Neste estudo a utilização deste tipo de passagem, característico por se adequar a uma vasta gama de espécies (Larinier, 2002) nomeadamente as potamodromas (Santo, 2005); demonstrou ser adequada à passagem do barbo Ibérico. Pelo que, dada a ubiquidade desta espécie na maioria dos rios Portuguese (Magalhães, 1992), a implantação deste tipo de passagem para peixes demonstra ser uma boa solução para facilitar a transposição para montante desta espécie.

Dada a irregularidade espacial e temporal de disponibilidade de água característica dos rios Portuguese, consequência da influência Mediterrânea dominante (Gasith e Resh 1999), a concepção de passagens para peixes por bacias sucessivas só com orificios de fundo, pode por conseguinte ser uma boa solução, considerando o baixo caudal de escoamento necessário ao seu funcionamento. No entanto as possíveis desvantagens associadas à utilização dos orifícios de fundo, como por exemplo a sua maior propensão para possíveis bloqueamentos pela presença de lixo ou detritos (Larinier, 2002; Santo, 2005), poderão ser limitantes ao bom funcionamento deste dipositivo, aos quais estão associados custos de manutenção que podem ser bastante elevados.

O presente trabalho contribui para o aumento do conhecimento sobre o comportamento do barbo Ibérico durante a sua movimentação para montante numa passagem para peixes por bacias sucessivas. A importância da sua aplicabilidade aquando da concepção deste tipo de dispositivos com vista a esta espécie, aponta para a necessidade acrescida da continuação de estudos focados na resposta comportamental desta espécie perante outros cenários hidráulicos, bem como de outras espécies de semelhantes capacidade natatórias, para as quais exite pouca infoprmação neste âmbito (Katopodis, 2005; Stuart and Mallen-Cooper, 1999).

Simultaneamente, este trabalho aponta igualmente para a necessidade de desenvolver estudos que analisem a relação benefícios/custos da implantação de determinadas geometrias de passagens para peixes bem e a sua adaptabilidade às espécies/rios Portugueses. Tornando-se por conseguinte essencial a existência de programas de manutenção e gestão permanentes, de forma a assegurar a eficácia das passagens para peixes.

6.2. EFEITOS DA VELOCIDADE DA ÁGUA E DA TURBULÊNCIA NO COMPORTAMENTO DO BARBO IBÉRICO (*LUCIOBARBUS BOCAGEI* STEINDACHNER 1865) NUM PROTÓTIPO EXPERIMENTAL DE UMA PASSAGEM PARA PEIXES POR BACIAS SUCESSIVAS.

Neste estudo foram analisados os efeitos da velocidade da água, da turbulência e respectivos descriptores (energia cinética da turbulência e tensões de Reynolds) nos movimentos para montante do barbo Ibérico num protótipo experimental de uma passagem para peixes por bacias sucessivas. Em simultâneo foram analisadas possíveis diferenças a nivel da resposta comportamental dos epécimes para as diferentes classes de dimesnões testadas.

A utilização do velocimetro acoustico Doppler (ADV), permitiu a caracterização tridimensional dos campos de velocidade e das condições de turbulência criadas nas várias configurações testadas, possibilitando o entendimento das características hidráulicas do escoamento, urtilizadas por conseguinte, como variáveis explanatórias das respostas comportamentais dos vários espécimes durante a sua movimentação para montante na passagem para peixes.

As condições hidráulicas criadas pelas diferentes configurações testadas que variaram no caudal e dimensão dos orifícios de fundo, demonstraram ser adequadas à passagem para montante desta espécie. As velocidades máximas observadas (aproximadamente $0.80 m.s^{-1}$) enquadravam-se nas velocidades consideradas como adquadas à movimentação desta espécie (Larinier, 2002; Mateus *et al.*, 2008). As condições de turbulência criadas no interior das bacias, foram igualmente adequadas à manutenção da capacidade de natação e de sustentabilidade na coluna água pelos espécimes. Os valores máximos de energia dissipada por volume de água, indicador dos níveis de turbulência do escoamento, foram sempre inferiores a $150 W.m^{-3}$, valor máximo considerado por Larinier (2002), como adequado para as espécies ciprinicolas. Não obstante, a adequatibilidade das condições hidráulicas para a passagem dos espécimes, reflectida pelo elevado sucesso de passagem dos mesmos, o comportamento dos peixes foi fortemente determinado pelas mesmas. Apesar de fortemente condicionado pelo campo de velocidades criado, o comportamento dos peixes foi essencialmente afectado pelos níveis de turbulência existentes. A energia cinética da turbulência e as tensões de Reynolds actuantes ao nível do plano horizontal, demonstraram ser os factores proeminentes no condicionalismo do comportameno dos peixes, principalmente dos mais pequenos. A importância destes parâmetros na movimentação dos peixes, fora já reconhecida por outros autores como Odeh *et al.*, (2002) e Cada *et al.* (2000) que estudaram respectivamente, o efeito da turbulência e das tensões de Reynolds sobre os peixes, tendo identificado que o comportamento dos mesmos era extemamente susceptível e condicionado pelas variações da turbulência, particularmente pelas tensões de Reynolds.

Estes parâmetros emergem assim como factores chave a serem considerados aquando da concepção de uma passagem para peixes. Durante a sua travessia para montante os peixes nadam contra a corrente, o que devido ao gasto energético inerente a este processo os torna extremamente susceptíveis a qualquer tipo de perturbaçãoes. Elevados valores de turbulência, induzem a um aumento energético requerido, uma vez que destabilizam a capacidade natatória e equilibrio do peixe (Cada *et al.*, 1999; Pavlov *et al,* 2000). Dependendo da magnitude da accção turbulência, os peixes podem apenas sofrer uma desorientação relativamente à direcção do seu movimento, ou padecer de alguns danos físicos que em casos extremos podem levar à sua morte (Odeh *et al.*, 2002).

Salienta-se inda ofactodeos peixe idependentement do seutamanho permanecerem essencialmente junto ao fundo da bacia, apresentando um comportamento semelhante ao manifestado no seu habitat natural. Este aspecto, sustem a ideia defendida por vários autores (Kemp *et al.* 2006; Odeh *et al.*, 2002) de que os diferentes efeitos das condições hidráulicas no comportamento do peixes podem ser simluados e medidos em condições experimentais laboratoiriais.

O desenvolvimento de estudos futuros, que conjuguem as limitações biomecânicas das espécies e as características hidráulicas numa passagens para peixes, visando miminizar possíveis desorientações e elevados períodos de passagem dos peixes neste tipo de dispositivo de passagem é por conseguinte extremamente importante. A mofificação das características internas do escoamento por meio de implementação diferentes subtractos e análise das respectivas condições de velocidade e de turbulência em particular das tensões de Reynolds criadas, poderá ser uma solução a considerar. Dada a variabilidade encontrada na resposta comportamental dos espécimes de acordo com a sua dimensão, estudos futuros focados na determinação de limites máximos de turbulência tolerados por várias espécies e espécimes de diferentes dimansões, são igualmente de extrema importância. Estes facutarão informação determinante à concepção de uma passagem para peixes, cujo principio se baseia na projecção da mesma de modo a permitir a passagem da espécie mais desfavorecida, em termos de capacidade natatória (Santo, 2005).

6.3. PREFERÊNCIA DO BARBO IBÉRICO (*LUCIOBARBUS BOCAGEI* STEINDACHNER 1865) POR ORIFÍCIOS ALINHADOS OU DESALINHADOS NUM PROTÓTIPO EXPERIMENTAL DE UMA PASSAGEM PARA PEIXES POR BACIAS SUCESSIVAS

A eficiência de duas configurações, cuja variação incidiu no alinhamento dos orifícios de fundo (alinhados e desalinhados), para a passagem para montante do barbo Ibérico foi analisada, considerando duas classes de dimensões diferentes.

Numa perspectiva hidraúlica, ambas as configurações demonstraram estar bem estruturadas, apresentando regimes uniformes, indicadores de estabilidade hidráulica em todas as bacias (Larinier, 2002), permitindo o estudo comparativo das condições hidraúlicas criadas e o relacionamenmto das mesmas com os resultados comportamentais obtidos. Ambas as configuraçãoes permitiram a passagem para montante do barbo, no entanto a taxa de sucesso obtida na configuração com orificios alinhados foi baixa (28%) quando comparada com a obtida para a configuração com orifícios desalinhados (68%). Considerando que, para as espécies potamodromas a eficiência de uma passagem para peixes é geralemente consideranda aquando da passagem de um número subtancial da população existente (Porcher e Travade, 2002), conclui-se que a configuração com os orifícios desalinhados poderá ser considerada como eficiente à passagem desta espécie em detrimento da configuração com orificios alinhados. Este resultado apresenta-se como contraditórtio ao trabalho de Kim, 2001, no qual apesar de terem sido testados em simultâneo descarregadores de superfície e orifícios de fundo, o autor baseado na condições existentes nas designada zona descanso "*resting-areas*", propõe que o alinhamento dos orifícios e descarregadore de superfície poderão ser mais favoráveis à passagem pra montante dos peixes. A contradição de ambos os resultados, poderá resultar do facto de Kim (2001) fundamentar as suas conclusões apenas em dados hidráulicos, não tendo realizado experiencias com peixes, pelo que a relação entre as características biomecânicas das espécies bem como os factores condicionantes às respectivas capacidades natatórias e as características hidráulicas não foi estabelecida. Este factor pode então ser apontado como a principal razão para a desrepancia entre os seus resultados e os obtidos neste trabalho, evidenciando a necessidade de desenvolver estudos que conjuguem as características biomecanicas das espécies e as condições hidráullicas nas passagens para peixes, de forma a aumentar a veracidade dos resultados obtidos.

Apesar de verosimilhança entre os valores máximos de velocidade e de turbulência, especificamente da energia cinética da turbulência, da intensidade de turbulencia e das tensões de Reynolds, foi claramente notória a diferença entre a capacidade dos espécimes para ultrapassarem as condições hidráulicas existentes nas configurações com orifícios desalinhados e alinhados, em particular a dos peixes de menores dimensões que demonstraram significativas dificuldades em transpor a passagem na presença de orifícios alinhados. A relação entre o tamanho dos espécimes e a sua capacidade para ultrapassar as condições hidráulicas subjacentes ao escoamento numa passagem para peixes, emerge como um dos factores limitante à mesma, sendo por esse motivo a sua ponderação essencial aquando da concepção de uma passagem para peixes, tal como concluído por Slavick *et al.* (2009).

Considerando, que a maior diferença em termos hidráulicos entre estes dois tipos de configuração incidiu no padrão de escoamento criado, poder-se-á concluir que este foi um dos factores proeminetes à diferenciação anteriormente referida. A maior estabilidade do padrão de escoamento às variações do caudal de escoamento relativamente ao tipo de configuração testado, evidencia a importancia da adequação da configuração deste tipo de dispositivo às espécies alvo, factor determinante do padrão de escoamento existente que pode por vezes ser limitante à passagem dos espécimes. A compreensão do escoamento existente considerando as capacidades natatórias das espécies, é por conseguinte uma ferramenta importante durante o processo de selecção do "desenho" a adoptar de uma passagem para peixes. Semelhante conclusão foi apresentada por Rodriguez *et al.* (2006), no seu estudo incidente na avaliação do "desenho" de uma passagem para peixes por fendas verticais em termos da capacidade de natação dos peixes.

A evidente abrupta estratificação transversal de velocidades e de condições de turbulência nas bacias, ocorrente nas configurações com orifícios alinhados, poderá ser considerada como a principal causa para o baixo sucesso de passagem observado e do respectivo elevado tempo de transposição. O escoamento principal fortemente unidireccional com valores de velocidades e turbulência muito elevados, destacando-se de entre os últimos os elevados valores das tensões de Reynolds, parece ter actuado como factor impeditivo à passagem para montante dos espécimes. A capacidade de natação dospeixes bem como a sua estabilidade dependem fortemente das flutuações dos parâmetros hidráulicos, como da velocidade e da turbulência (Bunt, 2001; Lupandin, 2005; Odeh *et al.*, 2001). Perante os valores elevados destas variáveis existentes no escoamento principal, os espécimes enfretaram fortes dificuldades na manutenção do seu equilíbrio, devido ao acréscimo de energia para a manutenção do mesmo (Pavlov *et al.*, 2000), induzindo à desorientação dos peixes. Perante tais condições adversas, a existência de uma larga zona de recirculação caracterizada por valores significativamente inferiores de turbulência e velocidades, poderá ter funcionado comouma espécie de "armadilha" induzindo os peixes a permanecerem dentro da mesma, evitando assim as condições hidráulicas existentes no escoamento principal, aumentando por conseguinte o tempo de permanência nas bacia. A redução da capacidade dos índices reostácticos dos peixes em situações de baixas velocidadese turbulências (Lupandin, 2005), poderá ter influenciado fortemente o comportamento observado.Este fenómeno foi igualmente observado por Tarrade *et al.* (2008), durante um estudo experimental do escoamento turbulento numa passagem para peixespor fendas verticais, onde espécimes de pequenas dimensões demonstraram ficar “presos” nas zonas de recirculação evidenciando fortes dificuldades em atravessar rapidamente as várias bacias.

O desenvolvimento de estudos que visem a redução desta abrupta variação transversal de velocidades e de condições de turbulencia, deverão ser fortementes considerados para o aperfeiçoamento das configurações de dimensionamento das passagens para peixes. A introdução de obstáculos na zona de escoamento principal, visando a interrupção da continuidade do mesmo, permitindo a dissipação das condições de turbulência por toda a extensão da bacia poderá ser uma possivel solução, facultando a passagem para montante. Por outro lado, a impantação de obstaculos na zona de recirculação de modo a criar alguma turbulência e velocidades atractivas aos peixes induzindo à sua movimentação e consequentemente impedindo a ocorrência da sua permanência prolongada nessas zonas, poderá igualmente facilitar a movimentação dos espécimes, por redução da designada zona de “armadilha”.

6.4. ESTUDO DA EFICIÊNCIA DE UMA NOVA CONFIGURAÇÃO DE UMA PASSAGEM PARA PEIXES POR BACIAS SUCESSIVAS PARA O BARBO IBÉRICO (*LUCIOBARBUS BOCAGEI* STEINDACHNER 1865)

Tendo como base os resultados obtidos no trabalho anterior, neste trabalho foi avaliada a eficiência de duas configuraçõess, uma com orifícios alinhados e outra com orifícios desalinhados com uma barra deflectora; para a passagem para montante do barbo Ibérico com diferentes dimensões.

A introdução da barra deflectora no escoamento principal entre dois orificios de fundo alinhados, permitiu uma ligeira redução dos níveis de turbulência e velocidades, que tinham sido observados no trabalho anterior para condições de dimensionamento semelhantes. No entanto, não obstante dos valores reduzidos de velocidades e de turbulência encontrados, os quais foram igualmente inferiores aos observados no escoamento principal criado entre orifícios desalinhados, o sucesso de passagem dos peixes foi menor na situação de orifícios alinhados, demonstrando que apesar da introdução da barra deflectora esta configuração não é favorável para a passagem para montante dos peixes. À semelhança com o observado no trabalho anterior, aqui o padrão de escoamento demonstra ter sido o factor proeminente à diferenciaçãoda resposta comportamental dos espécimes de diferentes classes de dimensões, entre os dois tipos de configuração testados, corrobando novamente a ideia defendida por Rodriguez *et al.* (2006), de que a compreensão do escoamento existente considerando as capacidades natatórias das espécies, é por conseguinte uma ferramenta importante durante o processo de selecção do "desenho" a adoptar de uma passagem para peixes. Apesar da criação de um maior número de zonas de descanso, e das menores velocidadese condições de turbulência criadas, a localização do escoamento principal na configuração de orifícios alinhados com uma barra deflectora, demonstrou ser mais impeditivo à passagem para montante principalmente os de maiores dimensões. Este resultado surge em contradição com os resultados obtidos nos trabalhos anteriores onde os peixesde menores dimensões manifestaram maiores dificuldadesem transpor a passagem. No entanto este poderá estar relacionado com a mior capacidade restáctica dos indivíduos mais pequenos. Capel e Garcia de Jálon (1999) verificaram que os espécimes de barbos com menores dimensões apresentavam uma capacidade reostática superior à dos indivíduos de maiores dimensões, perante condições naturais. Considerando que o escoamento principal entre dois orifícios alinhados com a barra deflectora ocupava prncipalmente a parte central da bacia, os peixes ao passarem o orificio debatiam-se imediatemente com maiores velocidades, as quais pareceram coibir a movimentação para montante dos peixes de maiores dimensões, estimulando por outro lado a passagem do peixes mais pequenos.Perante estas condições os peixes, independentemente do tamanho, demonstraram um elevado nível de desorientação, o qual influenciou fortemente o baixo sucesso de passagem observado.

Os resultados obsevados, evidenciam fortemente a necessidadede desnvolver estudos que conjuguqem as capacidades biomecânicas das diferentes espécies e as características do escoamento, através da testagem de diferentes tipos de geometrias. A relevância da diferenciação intra-especificas das espécies a qual deverá ser igualmente considerada aquando da concepção do dimensionamento de uma passagem para peixes, é igualmente evidente.

6.5. CONSIDERAÇÕES FINAIS

O entendimento entre as capacidades biomecânicas do barbo Ibérico e as características hidráulicas numa passagempara peixes por bacias sucessivas para diferentes configurações geométricas foi abordado neste estudo. Dada a enormidade de váriaveis intrínsecas a este processo e a referida escassez de informação sobre critérios de dimensionamento claramente definidos e correctamente relacionados com a ictiofauna, durante o desenvolvimento deste estudo surgiram várias questões relacionadas com a direcção a seguir, pelo que o seu dsenvolvimento foi um desafio difícil.

Este facto, juntamente com os resultados obtidos neste trabalho, evidencia a necessidade acrescida na continuidade de desenvolver trabalhos nesta área, pelo que são aqui indicados alguns aspectos passíveis de investigação em futuras pesquisas.

Em relação à abordagem das características hidráulicas do escoamento verifica-se a necessidade do estudo detalhado de outros tipos e geometrias de passagens para peixes por bacias sucessivas, incidindo na influência da declividade do canal, do tipo de deflector, do tamanho do canal, da relação comprimento/largura das bacias, dos caudais de descarga, entre outros, nos padrões de turbulência do escoamento.

Numa perspectiva de índole mais biológicas, deverão ser realizados estudos focados noutras espécies, com diferentes apacidades biomecânicas mas igualmente com baixa capacidade natatória, visto a escassezde informação sobre o comportamento e adpabilidade destas espécies às condições hidráulicas existentes neste tipo de dispositivos para passagem para peixes. Considerando a diversidade de espécies existentes, o estudo do comportamento para aumentar a informação disponível importante para o estabelecimento de critérios de dimensionamento de passagens para peixes adequados ao maior número de espécies possível.

Perante os resultados obtidos, com base em avaliações biológicas qualitativas e informações da literatura, verifica-se que a energia cinética da turbulência e as tensões de Reynolds podem ser bons indicativos da turbulência no comportamento dos peixes. O estudo detalhado e mais aprofundado do impacto destes parametros deverá por conseguinte ser realizado, considerando varias espécies. Devendo incorporar técnicas de marcação dos espécimes, que contribuirão fortmente para a obtenção de informação sobre os padrões de movimentação dos peixes durante a sua passagem por este tipos de dispositivos hidráulicos, face a diferentes condições hidráulicas. Paralelamente, será necessário estipular os valores máximos dos mesmos tolerados por diversas espécies com diferentes classes de dimensão para serem confrontados com as características hidráulicas de cada estrutura de transposição, visando a optimização destes sistemas, obtida através da conciliação simultânea de factores biológicos, hidráulicos e econômicos.

O desenvolvimento deste trabalho a nível laboratorial demonstrou ser adequado ao estudo dos efeitos das caracteristicas hidráulicas no comportamento dos peixes numa passagem para peixes. Deste modo, deverá ser dada continuidade a estudos experimentais a nível laboratorial com desenvolvimento simultâneo no campo, para uma maior complementariedade e consequente veracidade dos resultados obtidos.

As informações hidráulicas obtidas em estudos experimentais devem ser então utilizadas para calibrar os modelos computacionais do escoamento, cujo grau de confiabilidade aumenta com o aumento da informação disponível.

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