Corner and sloped culvert baffles improve the upstream passage of adult European eels (*Anguilla anguilla*)

L. R. Newbold[a*], P. Karageorgopoulos[b], P. S. Kemp[a]

[a] The International Centre for Ecohydraulics Research, Faculty of Engineering and the Environment, University of Southampton, Southampton, UK.

[b] Environment Agency, Guildbourne House, Worthing, UK.

* Corresponding author

Tel: (+44) 7792 552063

Email: lre105@soton.ac.uk

Address: The International Centre for Ecohydraulics Research, Faculty of Engineering and the Environment, University of Southampton, Highfield, Southampton, SO17 1BJ, UK.

Abstract

Installation of baffles intended to improve fish passage through culverts can reduce discharge capacity and trap debris, increasing flood risk. A sloping upstream face may reduce this risk, but new designs must be tested for fish passage efficiency. The European eel (*Anguilla anguilla*) is a critically endangered species, yet the suitability of even common baffle types to aid upstream movement has not been tested. This study compared the water depth, velocity, turbulent kinetic energy (TKE), and upstream passage performance of adult yellow-phase eels, between three 6 m long culvert models: smooth and unmodified (control); containing corner baffles (treatment 1); and with prototype sloped baffles installed (treatment 2). Passage of individual fish was assessed during 25 one-hour trials per model. Performance was quantified as entrance efficiency, number of entries per fish, passage efficiency, and overall efficiency. Total and passage delay, and successful passage time were also evaluated. Despite some individuals being able to swim against unexpectedly high water velocities (> 1.5 m s^{-1} for 4 m), passage performance in the control was poor, with an overall efficiency of 28%. Compared to the control, both treatments increased the mean centreline water depth by approximately 0.11 m, created heterogeneous flow conditions with low velocity resting areas, and reduced maximum velocities. As a result, entrance rate and all efficiency parameters were higher for the treatments than for the control (overall efficiency = 84%), despite longer passage delay. The TKE was slightly higher in treatment 2 than 1, but there was no difference in water depth or overall efficiency. The findings show that both corner and sloped baffles can mitigate for impeded upstream adult eel movement. The extent to which the sloping upstream face will improve debris transport should be explored further.

Keywords: Anguilliforms; waterway crossings; fish passage; river restoration; hydrodynamics.

1. Introduction

Culverts installed to convey watercourses under roads, railways and other infrastructure provide a less costly alternative to bridges. The river channel is usually constricted through a box, arch or pipe, with low channel roughness to maximise hydraulic capacity and reduce the probability of sediment and debris accumulation (Clay, 1995). However, rapid water velocities under high flows, insufficient depth at low discharge, and perching of the culvert outlet due to scouring of the downstream river bed, can fully or partially block upstream movement of aquatic organisms, including fish (Larinier, 2002). As a consequence, access to essential habitat (e.g. for spawning, feeding or rearing: Gibson et al., 2005; Sheer and Steel, 2006) is impeded and upstream fish species richness and abundance reduced (Burford et al., 2009; Franklin and Bartels, 2012; MacPherson et al., 2012).

In recognition of the impact culverts can have on fish passage, design criteria now commonly include recommendations to maintain ecological connectivity (e.g. Balkham et al., 2010; Schall et al., 2012). Where watercourses support migratory fish, new culverts should meet hydraulic criteria for passage, based on the swimming and leaping ability, and body depth, of the target species (Furniss et al., 2006; Caltrans, 2007; Armstrong et al., 2010; Barnard et al., 2013). At impassable culverts, the installation of retrofits can enable fish passage. When perched, weirs downstream of the outlet increase the tailwater depth, facilitating entry. Placement of bed substrate or baffles within the culvert lowers the water velocity, increases depth, and provides resting areas for fish moving upstream (e.g. Rajaratnam et al., 1988; 1989; Ead et al., 2002; Balkham et al., 2010; Feurich et al., 2011). A number of common baffle designs exist for different culvert types (overview in Armstrong et al., 2010). The corner baffle is often favoured in pipe culverts where passage of a range of species is required (Armstrong et al., 2010; Barnard et al., 2013). These are weir type baffles with the crest tilted by 10-20°, leaving one culvert wall unobstructed to facilitate the downstream movement of sediment and debris (Olsen and Tullis, 2013; Barnard et al., 2013).

Small diameter culverts in urbanised areas are widespread in Europe and baffle installation can reduce discharge capacity and trap debris, increasing flood risk (Barnard et al., 2013; Armstrong et al., 2010). A sloped upstream baffle face may reduce this risk by facilitating debris flow, but few studies have examined the suitability of this option for fish passage or culvert hydraulics (see Dupont, 2009 for fish passage, and Stevenson et al., 2008 for hydraulic analysis). Brown trout (*Salmo trutta*) were observed moving upstream through alternating sloped baffles, but passage efficiency was not quantified (Dupont, 2009). Computational fluid dynamic (CFD) modelling predicted higher intensities of turbulence downstream of wedge shaped spoiler baffles than a traditional block shaped design of equal height (Stevenson et al., 2008). It was assumed this would negatively influence fish passage but no biological testing was conducted.

Historically, culvert baffle design was driven by the requirements of salmonids, predominantly in North America, where considerable research has evaluated upstream movement of adults and more recently juveniles (e.g. Dane, 1978; Powers et al., 1997; State Coastal Conservancy, 2004; Pearson et al., 2006; Mueller et al., 2008; Burford et al., 2009; WSDOT, 2012). Worldwide, culvert design for passage of non-salmonid species is gaining attention (e.g. Neotropical fish in Brazil [Makrakis et al., 2012] and inanga [*Galaxius maculatus*] in New Zealand [Franklin and Bartels, 2012]). In Europe, providing and maintaining overall ecological connectivity is a key component of the Water Framework Directive (EC, 2000), but mitigating for the impact of a high density of culverts on multiple species has not been widely considered. For example, a recent attempt to identify barriers to fish movement in England and Wales did not include culverts (Environment Agency, 2010), despite a high abundance of these structures.

The European eel (*Anguilla anguilla*) is considered critically endangered due to a 95-99% decline in recruitment since the 1980s (Freyhof and Kottelat, 2010; ICES, 2013). Barriers to the upstream migration of juvenile eels (elvers) (Moriarty and Dekker, 1997; Feunteun, 2002), and dispersal of resident adults (yellow eels) (Ibbotson et al., 2002; Feunteun et al., 2003), have likely contributed to this decline. In 2007, the European Union adopted council regulation number 1100/2007 for establishing recovery measures for the European eel. Member states are required to implement eel management plans, which include the provision of passage routes at structures likely to impede migration. Recently, laboratory (e.g. Russon and Kemp, 2011) and field-based (e.g. Calles et al., 2012; Piper et al., 2012) experiments have been conducted to quantify swimming performance and behaviour at dams and weirs to improve eel pass designs. As yet there has been little consideration of the impact of culverts on eel movement, with no published studies quantifying passage efficiency (with or without baffles), and little mitigation guidance provided (e.g. Porcher, 2002; Environment Agency, 2011). For example, in the UK, maximum culvert water velocity criteria are provided for brown trout, Atlantic salmon (*Salmo salar*), and other non-salmonid fish species grouped together, without consideration of anguilliforms (Armstrong et al., 2010).

It is often assumed, but not tested, that species with a weak burst swimming performance, including the European eel, will be able to pass a mean cross sectional velocity designed for faster swimming fish by utilising the lower velocity areas close to the culvert wall (e.g. Scottish Executive, 2000).

The suitability of even common baffle designs for eels remains untested, and minimal data is available on the influence of sloped baffles on culvert hydraulics or fish passage. Therefore, this study compared the hydrodynamic characteristics and passage performance for upstream moving yellow eel in three full-scale model culvert designs. The pipes were smooth and unmodified (control) or with either corner baffles (treatment 1) or prototype sloped baffles (treatment 2) installed.

2. Methods

2.1. Fish collection and maintenance

Yellow phase (non-migratory) European eels (*n* = 75, mean ± SE total length = 439 ± 11 mm, mass = 161 ± 14 g) were collected from the River Meon, Hampshire, using pulsed DC backpack electrofishing equipment on 11 July and 2 August 2011, and transported in aerated containers to the International Centre for Ecohydraulics Research laboratory, University of Southampton (< 1 h transport time). Fish were held in an aerated and filtered 3000 L tank, filled with de-chlorinated water and kept at ambient temperature in an unheated building (mean ± SE = 18.50 ± 0.04 °C). Water changes (approximately 20%) were conducted every week to maintain a high water quality (NO_3 < 50 mg L^{-1}, NO_2 < 1 mg L^{-1}). Trials took place between 15 July and 10 August 2011, and eels were returned to the River Meon on 5 and 18 August 2011 with no mortality.

2.2. Experimental setup and protocols

Experimental trials were performed in a large re-circulatory outdoor flume with a trapezoidal cross section (50 m long, 2.1 m wide at the substrate, 0.5 m deep). Discharge was maintained at 66 L s^{-1} during all trials, using an electrically driven centrifugal pump and adjustable inlet gate and outlet weir. A 1.2 m diameter, 6 m long, smooth, high density polyethylene culvert was cut along the horizontal axis, painted white to facilitate filming, and installed on a 2% slope, 38 m downstream of the flume inlet (Fig. 1a). The installation created a lip (0.10 m high) from the flume floor to the culvert base, which was reduced by half using mixed diameter rock substrate. Screens (10 mm square mesh) were fitted 3.8 m downstream and 2.8 m upstream of the culvert to contain fish within the test area.

In treatment 1, five corner baffles (0.15 m high, 0.87 m wide, Fig. 1a and b) were constructed of 10 mm plywood and installed approximately 1 culvert diameter apart (1 m spacing), and with a baffle height of approximately 0.15 times culvert diameter (within the recommended range for pipe culverts: Caltrans, 2007; Hotchkiss and Frei, 2007). Baffles extended from the right wall of the culvert, when viewed facing downstream, with a crest angle of 10° from horizontal. For treatment 2, prototype sloped baffles were created by adding a sloping 0.4 m long twin-wall polycarbonate sheet to the upstream face of the corner baffles. This spanned between the crest and the culvert floor at an average angle of 20° (Fig. 1c).

Eel passage was evaluated in 25 trials, each using a single fish, per culvert design (total = 75 trials). Fish were allowed at least one hour to acclimatise to flume conditions in a perforated container located upstream of the test area (mean ± SE temperature = 18.52 ± 0.19 °C). An individual was then released 3 m downstream of the culvert outlet in an area of low velocity. Trials were ended after 60 min or when a fish successfully exited the culvert upstream. Experiments were completed during the night (21:45 - 04:00 BST) and filmed using overhead low light cameras under infrared illumination (850 nm). At the end of each trial the eel was anaesthetised in 2-phenoxyethanol solution (1%) and total length (mm) and mass (grams) recorded.

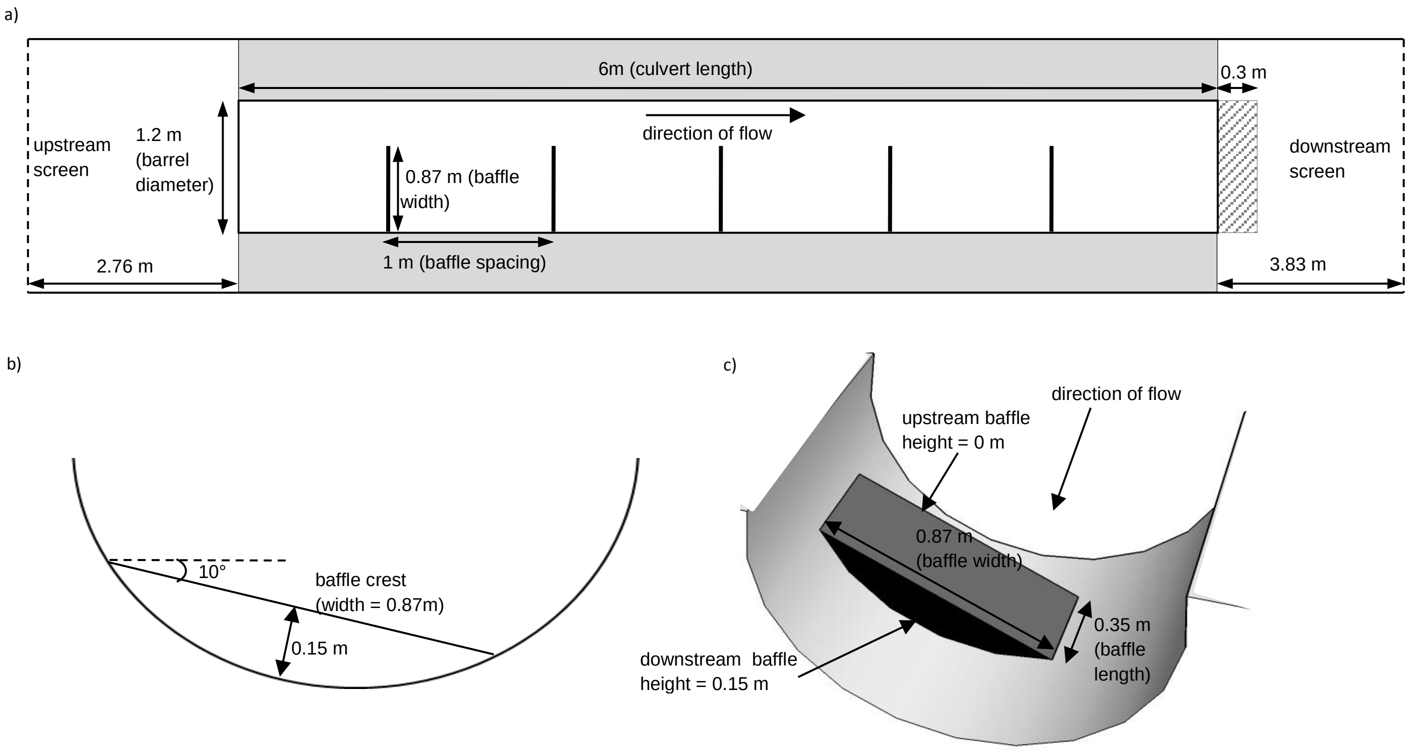

Figure 1. (a) Plan view of the model culvert and test area used to evaluate European eel passage performance. The culvert was installed 38 m downstream from the inlet of a large trapezoidal open channel flume (50 m long, 2.1 m wide at substrate, 0.5 m deep). Three designs were assessed: unmodified (control), or with corner baffles (treatment 1, illustrated) or prototype sloped baffles (treatment 2) installed. The hatched area at the outlet represents the approach zone (protruding 0.3 m downstream of culvert outlet).

(b) Corner baffle design as viewed looking upstream along the culvert. Baffle width is equal to the 0.87 m crest and baffle length to the 10 mm plywood.

(c) Three dimensional diagram of sloped baffle. The slope was created by fitting a flexible 0.4 m longtwin-wall polycarbonate sheet to the upstream face of the corner baffles. This spanned between the baffle crest and the culvert floor at an average angle of 20°, creating a 0.35 m baffle length.

2.3. Hydraulic conditions

Water depth in each baffle treatment was measured along 41 transects perpendicular to the flow. Due to greater flow homogeneity in the control, measurements were taken at a coarser resolution, at 3 equidistant points along 11 transects (see Fig. 2 for sample locations). The mean centreline depth was calculated for each culvert design, not including data collected above the sloping baffle face.

Velocity was measured at 60% of water depth at each sample point. For the two baffle treatments, a downward facing Acoustic Doppler Velocimeter (ADV, Nortek AS, Oslo, Norway) enabled collection of mean (± SD) longitudinal (*u*), lateral (*v*) and vertical (*w*) water velocity at each point. Data was collected at 50 Hz for 90 s, with a sample depth of 3.1 mm. Post collection, spurious data were filtered in each flow direction using a maximum/minimum threshold filter. Thresholds were calculated as in Cea et al. (2007) as: $u_{min} / u_{max} = \bar{u} \pm \sqrt{2\ln(n)}\,\sigma_u$, where n is the number of data points, σ the standard deviation of velocity and $\bar{u}$ the mean longitudinal velocity. As water depth in the control was insufficient to allow use of an ADV, mean (10 s) longitudinal water velocity and standard deviation were measured using an electromagnetic flow meter (Model 801, Valeport, Totness, UK).

In both treatments the turbulent kinetic energy (TKE) was calculated at each sample point as: TKE (J m^{-3}) = $0.5 \cdot \rho \cdot (\sigma_u^2 + \sigma_v^2 + \sigma_w^2)$, where ρ is the density of water (1000 kg m^{-3}), and the standard deviation of velocity is split into the three directional components. The TKE was chosen as a dimensional number that can be used to directly compare results with other laboratory and field studies (Lacey et al., 2011). Fluctuations in flow were highest in the longitudinal and lateral directions. As the TKE could not be calculated for the control, σ_u was used to compare fluctuations about the mean longitudinal velocity between the three culvert designs. The $\bar{u}$ and TKE at each point were plotted in ArcGIS 9.3 (ESRI, Redlands, USA) and interpolated using an inverse distance weighted method (power = 2, search radius = 12 points).

2.4. Eel passage performance

An approach to the culvert was defined as movement to within 0.3 m of the outlet. Passage performance was quantified as: 1) entrance efficiency (% of approaching eels that entered the culvert with at least part of their body); 2) number of entries per fish; 3) passage efficiency (% of those eels that entered the culvert that exited upstream); and 4) overall efficiency (% of approaching eels that exited upstream). Delay was split into total and passage delay, measured as the duration (min) between first culvert approach or entry, respectively, and upstream exit. Successful passage time was the duration (sec) between final entry into the culvert and exit upstream. Behaviour was recorded as: i) whether individuals ascending the control culvert utilised the lower velocity edge area; ii) the number of low velocity areas between consecutive baffles utilised by each eel during ascent of both treatments; and iii) the percentage of total culvert entries during each treatment (count for all individuals combined) that resulted in retreat downstream to the flume before passing the first baffle upstream of the culvert outlet.

2.5. Statistical analysis

To evaluate the effect of baffle type on water depth, the centreline depths at each transect, not including those located on the sloped baffle face, were compared between treatment 1 and 2 using a Wilcoxon signed-rank test.

To assess the effect of eel length and culvert design on the number of times individuals entered the culvert, a negative binomial regression with a log link function was used (McCullagh and Nelder, 1983; Hilbe, 2008). The count was converted to an entry rate to account for variation in time spent downstream of the culvert, by including the natural log of available time (i.e. 60 min or time between release and upstream passage) as an offset variable. Model fit was assessed using the likelihood ratio chi-square test and by examining deviance residuals. Significance of regression coefficients were assessed by the Wald chi-square test.

Binary logistic regression was used to test for effects of eel length and culvert design on the passage and overall efficiencies, by evaluating the probability of passage success. Significance of the covariates was assessed using the Wald chi-square test. Leverage statistics and residual analysis were used to check validity of model assumptions (Zuur et al., 2010), and the model chi-square test, Nagelkerke R^2, and the Hosmer and Lemeshow test to examine model fit.

The influence of culvert design on total and passage delay and successful passage time were analysed using Kruskall Wallace and post-hoc Bonferroni corrected exact Mann-Whitney tests. All analysis was completed using IBM SPSS Statistics version 19 (IBM Corp, Armonk, USA).

3. Results

3.1. Hydraulic conditions

The mean centreline water depth was 8.55 cm in the control, compared to 19.62 and 19.89 in treatment 1 and 2, respectively. There was no difference between the centreline water depth in treatment 1 and 2 (Wilcoxon z = -1.13, P = 0.26).

The centreline mean longitudinal water velocity in the control increased from 0.71 m s^{-1} at the culvert inlet to a maximum of 1.69 m s^{-1} at the outlet (Fig. 2). The mean transect velocities for mid culvert and the outlet were 1.54 m s^{-1} and 1.56 m s^{-1}, respectively. In the treatments, high velocity areas were located immediately downstream of each baffle on the culvert left hand side. The maximum velocities recorded in treatment 1 and 2 were 1.31 and 1.42 m s^{-1}, respectively (Table 1). Treatment 2 had greater reverse flows in the low velocity areas between baffles on the right hand side of the culvert than treatment 1 (Fig. 2).

The mean standard deviation of longitudinal velocity in the control was 0.03 m s^{-1}, compared to 0.29 and 0.30 m s^{-1} in treatment 1 and 2, respectively. Areas of TKE greater than 200 J m^{-3} were common in both treatments, with peaks of over 600 J m^{-3}. Areas of higher TKE were present on the left hand side of the culvert in treatment 2 than 1 (Table 1, Fig. 3).

Table 1. The mean (with range in parenthesis) of the mean longitudinal water velocity ($\bar{u}$), standard deviation of longitudinal water velocity (σ_u), and turbulent kinetic energy (TKE) at each sample point in a 6 m long model culvert for three designs: unmodified and smooth (control), corner baffles (treatment 1), and sloped baffles (treatment 2). Data was collected at 33 points using an electromagnetic flow meter in the control and at 300 and 313 points using an Acoustic Doppler Velocimeter in treatments 1 and 2, respectively.

Culvert design	**Velocity ($\bar{u}$: m s^{-1})**	**SD velocity (σ_u: m s^{-1})**	**TKE (J m^{-3})**
Control	1.43 (0.71 - 1.69)	0.03 (0.00 - 0.08)	na
Treatment 1	0.4 (-0.36 - 1.31)	0.29 (0.03 - 0.79)	128.16 (2.25 - 546.74)
Treatment 2	0.4 (-0.63 - 1.42)	0.3 (0.04 - 0.89)	149.02 (2.15 - 870.22)

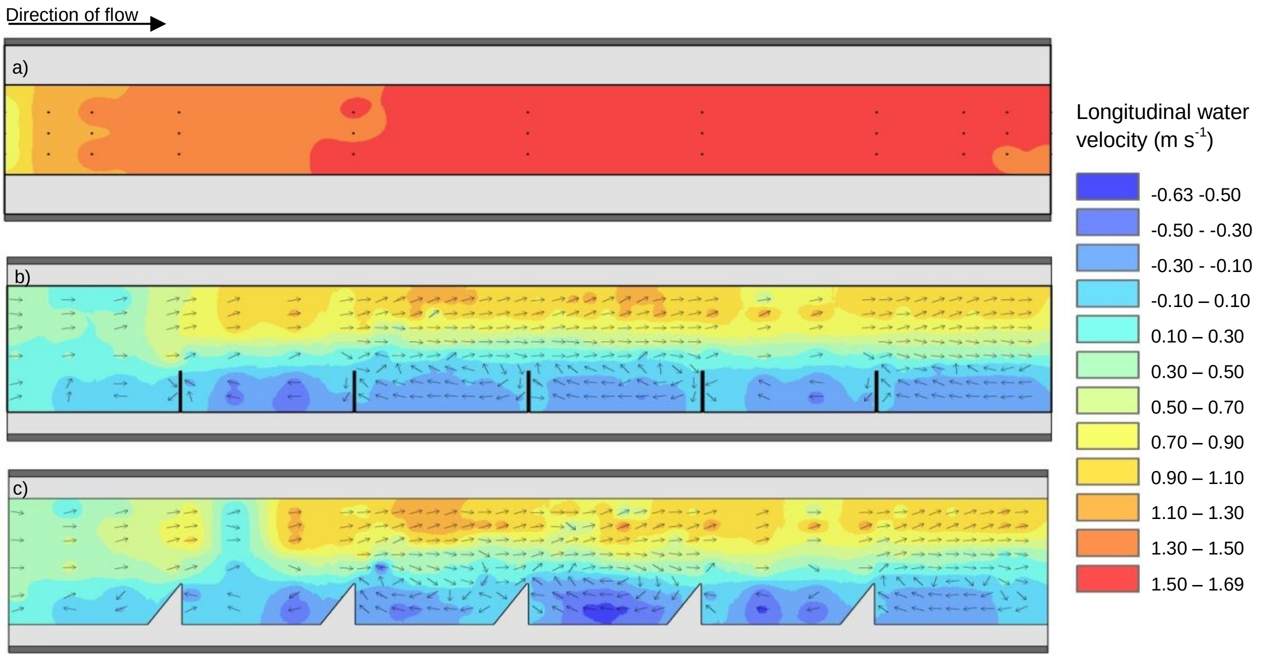

Figure 2. Plan view of the 60% depth mean longitudinal water velocity in a 6 m long, model culvert, for three designs: a) unmodified and smooth (control); b) corner baffles (treatment 1); and c) sloped baffles (treatment 2). Longitudinal velocity was collected at the points shown in the control with an electromagnetic flow meter, and at each arrow location in treatment 1 and 2 using an Acoustic Doppler Velocimeter. Arrows show the direction of flow, calculated from the longitudinal and lateral velocity components. Velocity was interpolated between points in ArcGIS.

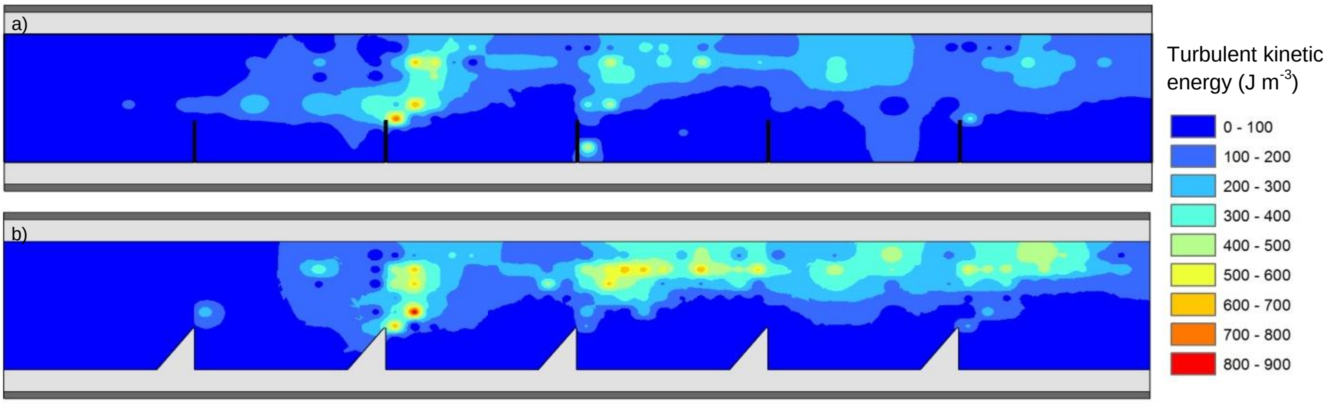

Figure 3. Plan view of 60% depth turbulent kinetic energy in a model, 6 m long, culvert with a) corner baffles (treatment 1), and b) sloped baffles (treatment 2) installed at 1 m intervals.

3.2. Eel passage performance

All fish approached the culvert and were included in passage analysis (Fig. 4). Entrance efficiency was 40, 92 and 100% for the control, and treatment 1 and 2, respectively. Entrance rate was affected by culvert design and was on average 9 and 13 times higher for treatment 1 and 2 than the control, respectively (Wald χ^2 = 21.17 and 34.35 respectively, df = 1, P < 0.001, Table 2). Entrance rate was not significantly different between treatment 1 and 2 (Wald χ^2 = 0.94, df = 1, P = 0.33), and was not affected by eel length (Wald χ^2 = 3.35, df = 1, P = 0.07).

Table 2. Results of a negative binomial regression model with a log link, where number of entrances to the culvert was the dependent variable, and culvert design (reference = control, 1 = corner baffles, 2 = sloped baffles) and eel length were the predictors. The regression coefficients (β) and associated SE, Wald Chi-Square P value, and odds ratio with 95% confidence intervals are reported.

			95% C.I. for odds ratio		
Variable	β (SE)	P	Lower	Odds ratio	Upper
Intercept	-9.65 (0.95)	<0.001	0.00	0.00	0.01
Culvert design = 1	2.18 (0.47)	<0.001	3.50	8.86	22.45
Culvert design = 2	2.59 (0.44)	<0.001	5.61	13.34	31.73
Length	0.004 (0.002)	0.07	1.00	1.004	1.008

Model likelihood ratio χ^2 = 38.40, df = 3, P < 0.001.

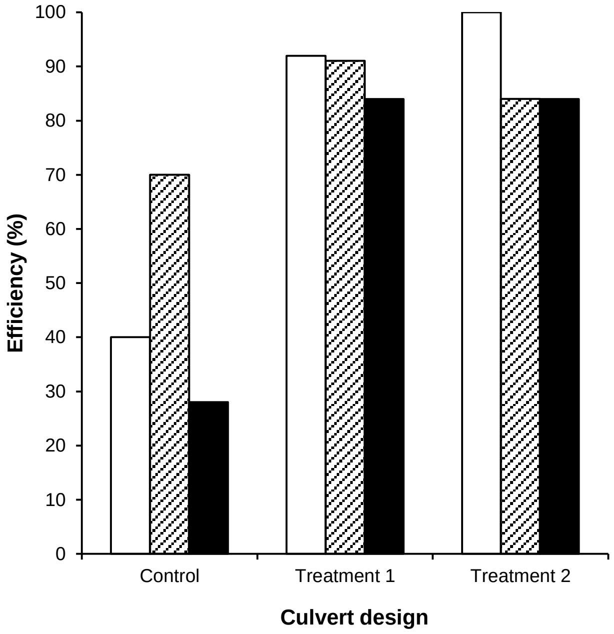

Figure 4. Summary of upstream European eel passage performance in three model culvert designs. Clear, hatched and solid bars, respectively, represent entrance (% of approaching eels that entered the culvert), passage (% of eels that entered and then exited upstream), and overall (% of all approaching eels that exited upstream) efficiency.

Passage efficiency was 70, 91 and 84% for the control, treatment 1, and treatment 2, respectively. There was no significant influence of culvert design or eel length on passage efficiency (model χ^2 = 7.26, df = 3, P = 0.06). The overall efficiency was 28% for the control, and 84% for both baffle treatments. Overall efficiency was effected by eel length, with larger eels more likely to pass upstream (Wald χ^2 = 7.02, df = 1, P < 0.01), and differed between culvert designs (Wald χ^2 = 16.59 df = 2, P < 0.001, Table 3). Overall efficiency was higher in both treatments than the control, but did not differ between treatment 1 and 2 (Wald χ^2 = 0.05, df = 2, P = 0.82).

Table 3. Results of a binary logistic regression model to assess the impact of culvert design and eel total on overall efficiency of yellow eel passage through an experimental culvert. The binary dependent variable was passage success and the influence of culvert design was analysed using a simple contrast (reference = control, 1 = corner baffles, 2 = sloped baffles). The regression coefficients (β) and associated SE, Wald Chi-Square P value and odds ratio with 95% confidence interval are reported.

			95% C.I. for odds ratio		
Variable	β (SE)	P	Lower	Odds ratio	Upper
Constant	-8.28 (2.87)	0.004		0.00	
Culvert design		< 0.001			
Treatment 1	3.11 (0.92)	0.001	3.70	22.53	137.31
Treatment 2	3.30 (0.88)	< 0.001	4.90	27.21	151.29
Length	0.02 (0.01)	0.009	1.00	1.02	1.03

Model χ^2 = 32.38, df = 3, P < 0.001, Nagelkerke R^2 = 0.50, Hosmer and Lemeshow χ^2 = 1.18, df = 8, P = 0.99.

Total delay did not differ between culvert designs (Kruskall Wallis χ^2 = 1.86, df = 2, P = 0.40). Passage delay varied between designs (Kruskall Wallis χ^2 = 7.11, df = 2, P < 0.05, Fig. 5), being longer in treatment 2 than the control (median = 3.17 versus 0.23 min; Mann-Whitney U = 28, P < 0.05). After Bonferroni corrections there was no significant difference between the control and treatment 1 (median = 0.65 min; Mann-Whitney U = 33.5, P = 0.03), or between the two baffle treatments (Mann-Whitney U = 174, P = 0.25).

Successful passage time differed between the culvert designs (Kruskall Wallis χ^2 = 17.06, df = 2, P < 0.01), being shorter for the control than treatment 1 (median = 14 versus 35 s, Mann-Whitney U = 5.5, P < 0.01) and 2 (median = 41 s; Mann-Whitney U = 3.0, P < 0.01). There was no difference between treatment 1 and 2 (Mann-Whitney U = 167.5, P = 0.18).

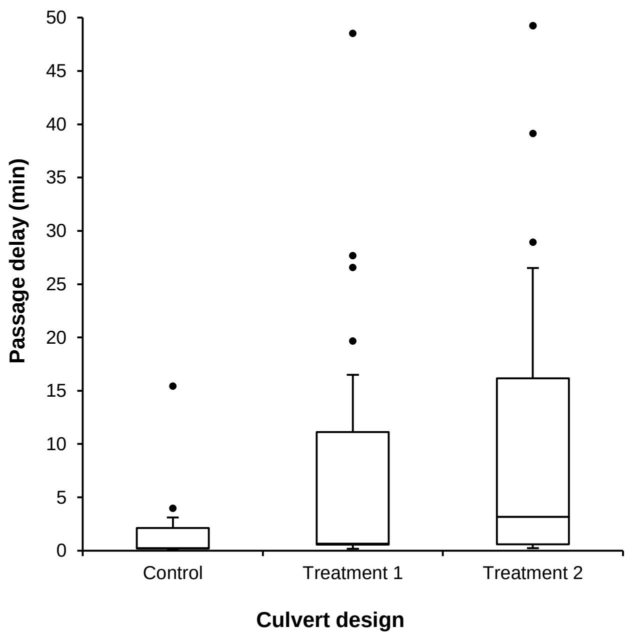

Figure 5. Passage delay (time between first culvert entrance and upstream passage) for three model culvert designs: smooth and unmodified (control), corner baffles (treatment 1) and sloped baffles (treatment 2). Data is shown as the median, interquartile range, whiskers at 1.5 x interquartile range or minimum, and outliers. The maximum trial duration was 60 min.

Only one eel swam the entire length along the control culvert wall where velocities were lowest. In both treatments, eels commonly moved away from the culvert left hand side to rest in the low velocity areas between consecutive baffles. All 5 of these areas were utilised by 52% of fish in both treatments, which tended to result in a longer successful passage time (Table 4). A total of 52 and 100 entries were made by the 25 fish in treatments 1 and 2, respectively. Of these, 54% (treatment 1) and 70% (treatment 2) resulted in retreat downstream to the flume before passage of the first baffle.

Table 4. The number of low velocity areas between consecutive baffles utilised by individual yellow eels during upstream ascent of a culvert fitted with corner (treatment 1) and sloped (treatment 2) baffles, and the mean time (with range in parenthesis) taken to pass the culvert (i.e. successful passage time).

	Treatment 1		Treatment 2	
Number of low velocity areas utilised	Frequency of fish	Successful passage time (s)	Frequency of fish	Successful passage time (s)
1	1	10 (na)	0	na
2	1	18 (na)	3	23 (14-34)
3	6	35 (28-49)	4	33 (24-45)
4	2	29 (26-32)	3	68 (57-84)
5	11	40 (21-54)	11	68 (29-326)

4. Discussion

Culverts have the potential to severely impede fish migration due to the creation of adverse hydraulic conditions (Warren and Pardew, 1998). In this study, the low overall efficiency of an unmodified culvert to pass yellow phase European eel upstream caused the structure to form a partial barrier to fish movement. Both corner and prototype sloped baffles were successful in improving entrance and overall efficiency compared to the unmodified culvert. Corner baffles are often recommended for other fish species (Armstrong et al., 2010; Barnard et al., 2013) and, therefore, may provide a valuable multi-species mitigation option at culverts that can be difficult to pass. At the discharge tested, the hydrodynamic conditions created by the sloped baffle design did not alter eel passage performance compared to the corner baffles. Water depth was also equal with corner and sloped baffles and the angled face may have the potential to improve transport of debris and thus reduce flood risk.

As eels have a relatively low burst swimming ability compared to many other fish species (McCleave, 1980; Environment Agency, 2011; Russon and Kemp, 2011), velocity barriers may disproportionally impede their movements. Velocities within the unmodified culvert were below the Environment Agency maximum criteria for adult brown trout, but at the maximum limit of eel swimming ability for the size range tested (reviewed in

Environment Agency, 2011). Thus, this likely contributed to the low overall efficiency (28%). Furthermore, at these high velocities time to fatigue would be short and passage through a much longer unmodified culvert with similar velocities would likely be impossible (Bainbridge, 1960; Katopodis and Gervais, 2012). The high velocities, low water depth, and outlet lip may have also reduced culvert entry. Although the outlet lip remained during both treatments, the two baffle designs successfully altered the hydrodynamic conditions to enhance entrance efficiency (92 and 100% for corner and sloped baffles, respectively).

Open channel flume studies can result in higher fish swimming speeds than achieved in swim chamber tests where the confined conditions prevent fish from exhibiting natural performance enhancing behaviours to maximise swimming speeds (Peake and Farrell, 2004; 2006; Tudorache et al., 2007). A model developed based on the results of swim chamber tests predicted a burst swimming ability of 1.18 to 1.27 m s^{-1} (90% confidence intervals: 0.97 to 1.48 m s^{-1}) for European eel within the range of body lengths (366 - 546 mm) and water temperatures (16.1 – 19.0 °C) used in the unmodified culvert trials (SWIMIT V 3.3. © Environment Agency, 2005, see Clough et al., 2004). Yet, a recent volitional study found that migratory 'silver' European eels (mean length = 660 mm) at an average temperature of 15 °C could actually traverse velocities of 1.75 to 2.12 m s^{-1} over a distance of about 1 m (Russon and Kemp, 2011). Swimming performance is lower for yellow than silver eels (Quintella et al., 2010), but in this study some fish as small as 366 mm successfully negotiated velocities exceeding 1.5 m s^{-1} along 4 m of the unmodified culvert, before reaching slower flows near the inlet.

The installation of baffles created higher levels of turbulence compared to the unmodified control. This is an inherent effect of using structures to reduce water velocity, and alternative designs also produce high intensities of turbulence immediately downstream of baffles (e.g. Morrison et al., 2009). Turbulent flow can reduce fish stability and swimming performance (Tritico and Cotel, 2010), and elevate energy expenditure (Enders et al., 2005). Fish with an elongated body morphology, such as eels and lamprey, are perhaps most likely to be destabilised (Liao, 2007), although this has not been quantified. Conversely, it has been suggested that they may, under certain conditions, be attracted to turbulent areas (Russon et al., 2010; Piper et al., 2012) and utilise reverse flows to minimise energy expenditure (Kemp et al., 2011). Although the TKE in both culvert treatments (200-400 J m^{-3}, with peaks of over 600 J m^{-3}) was considerably higher than levels demonstrated to increase juvenile Atlantic salmon swimming costs (Enders et al., 2005; 41.6 J m^{-3}), overall efficiency of eel passage was high. This suggests that any negative consequences for eel swimming performance were limited, and the improvement in passage performance compared to the control supports the use of baffles over the culvert length tested.

Baffle spacing and dimensions influence culvert hydrodynamics and determine flow capacity and fish passage success (Rajaratnam et al., 1988; 1989; 1990; Caltrans, 2007). The sloped baffle design created slightly higher TKE on the left hand side of the culvert than in the corner baffle model. This is analogous to the CFD modelled increase in turbulent flow downstream of wedge shaped spoiler baffles compared to oblong ones (Stevenson et al., 2008). Despite hydrodynamic differences between treatments, overall efficiency was equal, and entrance and passage efficiency were similar. However, the time from first culvert entry to exit upstream (passage delay) was greatest for the sloped baffle design. This was likely in part due to a longer successful passage time in treatments due to resting between baffles during ascent, an advantage that would enable passage of long culverts whilst minimising energetic expenditure. However, as passage delay differed between treatments and could be up to 50 minutes, other factors also likely contributed and further evaluation under alternative flows are recommended to improve understanding of the influence of hydrodynamics on passage performance. Hydrodynamic, physical, and other environmental factors can cause delay and reduce passage at anthropogenic structures by influencing behaviour (Rice et al., 2010, Kemp et al., 2011). The majority of culvert entries during both treatments resulted in downstream retreat before passage of the first baffle, which likely contributed to the greater passage delay than experienced in the control culvert. This was unlikely to be due to poor motivation or swimming ability, as approach efficiency was 100% and overall efficiency high for both treatments. It may have been an outcome of eel's natural tendency to seek cover (Edel, 1975; Tesch, 2003), resulting in exploration of the open channel flume and resting downstream of the first baffle encountered. It is also possible that the substrate oriented, thigmotactic, swimming behaviour described for eels (Russon et al., 2010; Russon and Kemp, 2011) may have discouraged passage when entry occurred on the side of the culvert where baffles were situated. In a similar experimental culvert study, substrate oriented inanga spent long periods of time swimming between full weir baffles without making upstream progress (Feurich et al., 2012). Thigmotactic behaviour was blamed for delay of downstream migrating European eels at an experimental overshot weir (0.20 m high) compared to an undershot weir, and the lower passage efficiency for the former (Russon and Kemp, 2011). Therefore, until further research into behaviour during passage of various designs has been conducted, including in situ field evaluation, baffles which cross the full culvert cross section are not recommended, due to the potential for further delay whilst searching for upstream routes.

The relative change in water depth compared to the control was equal for both baffle designs, indicating that the addition of a sloping upstream face onto the corner baffles did not reduce culvert flow capacity under the conditions tested. This design has the potential to reduce flood risk through reducing the likelihood of debris blockage, without decreasing discharge capacity beyond that caused by standard corner baffles, or reducing eel passage performance. Further laboratory trials followed by evaluation in situ are required to confirm the flood risk benefits.

5. Conclusion

Improving accessibility to suitable habitat upstream of barriers will assist in recruitment and population recovery of the European eel (White and Knights, 1997; Briand et al., 2005; Laffaille et al., 2009). Research has largely focused on improving upstream passage at dams and weirs as opposed to culverts (Feunteun, 2002). This study demonstrates that culverts with homogeneous flow and moderate water velocities can impede yellow eel movements. Where a new water crossing is required, a bridge or wide culvert with flow and substrate equal to local river conditions is recommended to encourage multi-species passage (Armstrong et al., 2010; Barnard et al., 2013). However, where this is not possible, or where existing culverts block eel movement, corner baffle installation may allow access to upstream reaches, and their current use for other species should also benefit yellow eel habitat access. Furthermore, the encouraging results described for the prototype sloped baffles justify further research and development. Evaluation of multi life stages including elver passage, hydraulic conditions, and debris transport at a range of culvert slopes, lengths, and flows is recommended to optimise the design. For migrating fish in their natural environment, the benefits of baffles may be even more pronounced, due to the strong desire to progress upstream, and field tests should be conducted to confirm eel behaviour and passage performance in situ.

Acknowledgements

This research was funded by the Environment Agency and an EPSRC PhD Doctoral Training Centre grant for the lead author. We thank Marnie Woods for technical assistance during the experimental period and Dave Hunter and Richard Redsull from the Environment Agency for supply and delivery of fish.

References

Armstrong, G.S., Aprahamian, M.W., Fewings, G.A., Gough, P.J., Reader, N.A., Varallo, P.V., 2010. Environment Agency fish passage manual: Guidance notes on the legislation, selection and approval of fish passes in England and Wales. Environment Agency, Bristol.

Bainbridge, R., 1960. Speed and stamina in three Fish. J. Exp. Biol. 37, 129-153.

Balkham, M., Fosbeary, C., Kitchen, A., Rickard, C., 2010. Culvert design and operation guide. CIRIA, London.

Barnard, R.J., Johnson, J., Brooks, P., Bates, K.M., Heiner, B., Klavas, J.P., Ponder, D.C., Smith, P.D., Powers, P.D., 2013. Water crossings design guidelines. Washington Department of Fish and Wildlife, Olympia, Washington.

Briand, C., Fatin, D., Fontenelle, G., Feunteun, E., 2005. Effect of re-opening of a migratory pathway for eel (*Anguilla anguilla*, L.) at a watershed scale. Bull. Fr. Pêche, Piscic. 378, 67-86.

Burford, D.D., McMahon, T.E., Cahoon, J.E., Blank, M., 2009. Assessment of trout passage through culverts in a large Montana drainage during summer low flow. N. Am. J. Fish. Manag. 29, 739-752.

Calles, O., Karlsson, S., Hebrand, M., Comoglio, C., 2012. Evaluating technical improvements for downstream migrating diadromous fish at a hydroelectric plant. Ecol. Eng. 48, 30-37.

Caltrans, 2007. Fish passage design for road crossings: An engineering document providing fish passage design guidance for Caltrans projects. California Department of Transportation.

Cea, L., Puertas, J., Pena, L., 2007. Velocity measurements on highly turbulent free surface flow using ADV. Exp. Fluids. 42, 333-348.

Clay, C.H., 1995. Design of fishways and other fish facilities, second ed. Lewis Publishers, CRC Press, Florida.

Clough, S.C., Lee-Elliott, I.E., Turnpenny, A.W.H., Holden, S.D.J., Hinks, C., 2004. Swimming speeds in fish: Phase 2. R&D Technical report W2-049/TR1, Environment Agency, Bristol.

Dane, B.G., 1978. Culvert guidelines: Recommendations for the design and installation of culverts in British Columbia to avoid conflict with anadromous fish. Fisheries and Marine Service, Vancouver.

Dupont, E., 2009. A new culvert design solves fish passage problems but is insufficient to restore normal brown trout *Salmo trutta* migration pattern. Proceedings of the 7th International Symposium of Ecohydraulics, Concepcion, Chile, 2009.

EC, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. Official J. Eur. Communities, L327, pp. 1–72.

Ead, S.A., Rajaratnam, N., Ketapodis, C., 2002. Generalized study of hydraulics of culvert fishways. J. Hydraul. Eng. 128, 1018-1022.

Edel, R. K., 1975. The effect of shelter availability on the activity of male silver eels. Helgoland Mar. Res. 27, 167-174.

Enders, E.C., Boisclair, D., Roy, A.G., 2005. A model of total swimming costs in turbulent flow for juvenile Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 62, 1079-1089.

Environment Agency, 2010. Mapping hydropower opportunities and sensitivities in England and Wales. Environment Agency, Bristol.

Environment Agency, 2011. Elver and eel passes: A guide to the design and implementation of passage solutions at weirs, tidal gates and sluices. Environment Agency, Bristol.

Feunteun, E., 2002. Management and restoration of European eel population (*Anguilla anguilla*): An impossible bargain. Ecol. Eng. 18, 575-591.

Feunteun, E., Laffaille, P., Robinet, T., Briand, C., Baisez, A., Olivier, J.M., Acou, A., 2003. A review of upstream migration and movements in inland waters by anguillid eels: towards a general theory, in: Aida, K., Tsukamoto, K., Yamauchi, K. (Eds.), Eel biology. Springer, Tokyo, pp 191-213.

Feurich, R., Boubée, J., Olsen, N.R.B., 2011. Spoiler baffles in circular culverts. J. Env. Eng. 137, 854-857.

Feurich, R., Boubée, J., Olsen, N.R.B., 2012. Improvement of fish passage in culverts using CFD. Ecol. Eng. 47, 1-8.

Franklin, P.A., Bartels, B., 2012. Restoring connectivity for migratory native fish in a New Zealand stream: effectiveness of retrofitting a pipe culvert. Aqat. Consv. 22, 489-497.

Freyhof, J., Kottelat, M. 2010. *Anguilla anguilla*, in: IUCN 2013. IUCN Red List of Threatened Species. Version 2013.2. Accessed online 18 March 2014 [www.iucnredlist.org].

Furniss M., Love M., Firor S., Moynan K., Llanos A., Guntle J., Gubernick R., 2006. FishXing Version 3.0. Corvallis, US Forest Service.

Gibson, R.J., Haedrich, R.L., Wernerheim, C.M., 2005. Loss of fish habitat as a consequence of inappropriately constructed stream crossings. Fisheries, 30, 10-17.

Hilbe, J.M., 2008. Negative binomial regression. Cambridge University Press, Cambridge.

Hotchkiss, R. H., Frei, C. M., 2007. Design for fish passage at roadway-stream crossings: Synthesis report. U.S. Department of Transportation, Publication No. FHWA-HIF-07-033, Washington D. C.

ICES, 2013. Report of the joint EIFAAC/ICES working group on eels (WGEEL). International Council for the Exploration of the Sea, ICES CM. 2013/AC0M:18, Copenhagen.

Ibbotson, A., Smith, J., Scarlett, P., Aprhamian, M., 2002. Colonisation of freshwater habitats by the European eel *Anguilla anguilla*. Freshw. Biol. 47, 1696-1706.

Katopodis, C., Gervais, R., 2012. Ecohydraulic analysis of fish fatigue data. River Res. Appl. 28, 444-456.

Kemp P.S., Russon I.J., Vowles A.S., Lucas, M.C., 2011. The influence of discharge and temperature on the ability of upstream migrant adult river lamprey (*Lampetra fluviatilis*) to pass experimental overshot and undershot weirs. River Res. Appl. 27, 488-498.

Lacey, R.W.J., Neary, V.S., Liao, J.C., Enders, E.C., Tritico, H.M., 2011. The IPOS framework: linking fish swimming performance in altered flows from laboratory experiments to rivers. River. Res. Appl. 28, 429-443.

Laffaille, P., Lasne, E., Baisez, A., 2009. Distribution of European eel in the Loire catchment, France. Ecol. Freshw. Fish. 18, 610-619.

Larinier, M., 2002. Fish passage through culverts, rock weirs and estuarine obstructions. Bull. Fr. Pêche Piscic. 364, 119-134.

Liao, J.C., 2007. A review of fish swimming mechanics and behavior in altered flows. Phil. Trans. Royal Soc. B. 362, 1973-1993.

MacPherson, L.M., Sullivan, M.G., Foote, A.L., Stevens, C.E., 2012. Effects of culverts on stream fish assemblages in the Alberta foothills. N. Am. J. Fish. Manage. 32, 480-490.

Makrakis, S., Castro-Santos, T., Makrakis, M.C., Wagner, R.L., Adames, M.S., 2012. Culverts in paved roads as suitable passages for Neotropical fish species. Neotrop. Ichthyol. 10, 763-770.

McCleave, J.D., 1980. Swimming performance of European eel (*Anguilla anguilla* (L.)) elvers. J. Fish Biol. 16, 445-452.

McCullagh, P., Nelder, J.A., 1983. Generalized linear models, second ed. Chapman and Hall, London.

Moriarty, C., Dekker, W., 1997. Management of European eel. Fisheries Bulletin (Dublin), 15, 1-110.

Morrison, R.R., Hotchkiss, R.H., Stone, M., Thurman, D., Horner-Devine, A.R., 2009. Turbulence characteristics of flow in a spiral corrugated culvert fitted with baffles and implications for fish passage. Ecol. Eng. 35, 381-392.

Mueller, R.P., Southard, S.S., May, C.W., Pearson, W.H., Cullinan, V.I., 2008. Juvenile coho salmon leaping ability and behaviour in an experimental culvert test bed. Trans. Am. Fish. Soc. 137, 941-950.

Olsen, A.H., Tullis, B.P., 2013. Laboratory study of fish passage and discharge capacity in slip-lined, baffled culverts. J. Hydraul. Eng. 139, 424-432.

Peake, S.J., Farrell, A.P., 2004. Locomotory behaviour and post-exercise physiology in relation to swimming speed, gait transition and metabolism in free-swimming smallmouth bass (*Micropterus dolomieu*). J. Exp. Biol. 207, 1563-1575.

Peake, S.J., Farrell, A.P., 2006. Fatigue is a behavioural response in respirometer-confined smallmouth bass. J. Fish. Biol. 68, 1742-1755.

Pearson, W.H., Southard, S.L., May, C.W., Skalski, J.R., Townsend, R.L., Horner-Devine, A.R., Thurman, D.R., Hotchkiss, R.H., Morrison, R.R., Richmond, M.C., Deng, D., 2006. Research on the upstream passage of juvenile salmon through culverts: Retrofit baffles. Final report for the Washington State Department of Transportation. WSDOT Agreement No. GCA2677. Battelle Memorial Institute, Washington D.C.

Piper, A.T., Wright, R.M., Kemp, P.S., 2012. The influence of attraction flow on upstream passage of European eel (*Anguilla anguilla*) at intertidal barriers. Ecol. Eng. 44, 329-336.

Porcher, A.P., 2002. Fishways for eels. Bull. Fr. Pêche Piscic. 364, 147-155.

Powers, P., Bates, K., Burns, T., Gowen, B., Whitney, R., 1997. Culvert hydraulics related to upstream juvenile salmon passage. Washington Department of Fish and Wildlife, Report to Washington Department of Transportation. Project No. 982740. Olympia, Washington.

Quintella, B.R., Mateus, C.S., Costa, J.L., Domingos, I., Almeida, P.R., 2010. Critical swimming speed of yellow- and silver-phase European eel (*Anguilla anguilla*, L.). J. Appl. Ichthyol. 26, 432-435.

Rajaratnam, N., Katopodis, C., Lodewyk, S., 1988. Hydraulics of offset baffle culvert fishways. Can. J. Civ. Eng. 15, 1043-1051.

Rajaratnam, N., Katopodis, C., McQuitty, N., 1989. Hydraulics of culvert fishways II: slotted-weir culvert fishways. Can. J. Civ. Eng. 16, 375-383.

Rajaratnam, N., Katopodis, C., Lodewyk, S., 1990. Hydraulics of culvert fishways IV: spoiler baffle culvert fishways. Can. J. Civ. Eng. 18, 76-82.

Rice S., Lancaster J., Kemp P.S., 2010. Experimentation at the interface of fluvial geomorphology, stream ecology and hydraulic engineering and the development of an effective, interdisciplinary river science. Earth Surf. Processes. 35, 64-77.

Russon, I., Kemp, P.S., 2011. Experimental quantification of the swimming performance and behaviour of spawning run river lamprey *Lampetra fluviatilis* and European eel *Anguilla anguilla*. J. Fish Biol. 78, 1965-1975.

Russon, I., Kemp, P.S., Calles, O., 2010. Response of downstream migrating adult European eel (*Anguilla anguilla*) to bar racks under experimental conditions. Ecol. Fresh. Fish. 19, 197-205.

Schall, J.D., Thompson, P.L., Zerges, S.M., Kilgore, R.T., Morris, J.L., 2012. Hydraulic design of highway culverts, third ed. U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-HIF-12-026, Washington D.C.

Scottish Executive, 2000. River Crossings and Migratory Fish: Design Guidance. Scottish Executive, Edinburgh. Accessed online 15 July 2013 [http://www.scotland.gov.uk/Topics/marine/science/Publications/publicationslatest/rivercrossings]

Sheer, M.B., Steel, E.A., 2006. Lost watersheds: barriers, aquatic habitat connectivity, and salmon persistence in the Willamette and Lower Columbia River basins. T. Am. Fish. Soc. 135, 1654-1669.

State Coastal Conservancy, 2004. Inventory of barriers to fish passage in California's coastal watersheds. Oakland, CA.

Stevenson, C., Kopeinig, T., Feurich, R., Boubée, J., 2008. Culvert barrel design to facilitate the upstream passage of small fish. NIWA Client Report: HAM2008-046, National Institute of Water and Atmospheric Research Ltd, Hamilton, New Zealand.

Tesch, F. W., 2003. The eel. Blackwell Science Ltd., Oxford.

Tritico, H.M., Cotel, A.J., 2010. The effects of turbulent eddies on the stability and critical swimming speed of creek chub (*Semotilus atromaculatus*). J. Exp. Biol. 213, 2284-2293.

Tudorache, C., Viaenen, P., Blust, R., De Boeck, G., 2007. Longer flumes increase critical swimming speeds by increasing burst-glide swimming duration in carp *Cyprinus carpio*, L. J. Fish. Biol. 71, 1630-1638.

WSDOT, 2012. Fish passage barrier inventory July 2012. Washington State Department of Fish and Wildlife, progress performance report for WSDOT fish passage inventory. Washington State Department of Transportation, Washington D.C.

Warren, M.L., Pardew M.G., 1998. Road crossings as barriers to small-stream fish movement. T. Am. Fish. Soc. 127, 637-644.

White, E.M., Knights, B., 1997. Dynamics of upstream migration of the European eel, *Anguilla anguilla* (L.), in the Rivers Severn and Avon, England, with special reference to the effects of man-made barriers. Fish. Manag. Ecol. 4, 311-324.

Zuur, A.F., Leno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. Method. Ecol. Evol. 1, 3-14.