RIVER RESEARCH AND APPLICATIONS
River Res. Applic. (2011)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/rra.1565

PERFORMANCE OF FISH PASSAGE STRUCTURES AT UPSTREAM BARRIERS TO MIGRATION

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ABSTRACT

Attraction and passage efficiency were reviewed and compared from 19 monitoring studies that produced data for evaluations of pool-and-weir, Denil, vertical-slot and nature-like fishways. Data from 26 species of anadromous and potamodromous fishes from six countries were separated by year and taxonomic family into a matrix with 101 records. Attraction performance was highly variable for the following fishway structures: pool-and-weir (attraction range=29–100%, mean=77%, median=81%), vertical-slot (attraction range=0–100%, mean=63%, median=80%), Denil (attraction range=21–100%, mean=61%, median=57%) and nature-like (attraction range=0–100%, mean=48%, median=50%). Mean passage efficiency was inversely related to mean attraction efficiency by fishway structure type, with the highest passage for nature-like fishways (range=0–100%, mean=70%, median=86%), followed by Denil (range=0–97%, mean=51%, median=38%), vertical-slot (range=0–100%, mean=45%, median=43%) and pool-and-weir (range=0–100%, mean=40%, median=34%). Principal components analysis and logistic regression modelling indicated that variation in fish attraction was driven by biological characteristics of the fish that were studied, whereas variation in fish passage was related to fishway type, slope and elevation change. This meta-analysis revealed that the species of fish monitored and structural design of the fishways have strong implications for both attraction and passage performance, and in most cases, existing data are not sufficient to support design recommendations. Many more fishway evaluations are needed over a range of species, fishway types and configurations to characterize, to optimize and to design new fishways. Furthermore, these studies must be performed in a consistent manner to identify the relative contributions of fish attraction and passage to overall fishway performance at each site. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: upstream fish migration; dams; fishways; attraction; passage efficiency; fishway monitoring

Received 29 October 2010; Revised 11 May 2011; Accepted 15 June 2011

INTRODUCTION

Upstream fish passage structures (i.e. fishways) are an integral and growing component of projects designed to restore river connectivity worldwide. When appropriately designed and situated, fishway structures allow upstream migrating fishes to bypass river barriers to reach river segments suitable for growth and reproduction (Clay, 1995; Jungwirth *et al*., 1998). A wide range of fish passage designs have been employed in an effort to facilitate upstream passage, from mechanical lifts/locks and dam gates to engineered fishways of a variety of types (e.g. Denil, vertical-slot, pool-and-weir and nature-like; Powers *et al*., 1985; Orsborn and Powers, 1986; Orsborn, 1987). Most fishways were originally designed to accommodate highly motivated species with strong swimming abilities, such as adult salmonids (Stuart, 1962, 1964). Broad diversity exists, however, among swimming abilities, migration windows and migratory motivation of target species to be passed—all of which are reflected in fish guidance, fish attraction and successful or complete movement through fish passage structures. Site-specific design variations in fishways related to slope, width, length, depth, configuration (i.e. shape, design and number of pools, traverses, orifices, baffles or roughness elements), entrance location and other factors also influence the effectiveness of attraction and passage for different fish species, but the relative contribution of these factors is difficult to separate and quantify, largely because of a lack of established and broadly applied methods (Castro-Santos *et al*., 2009).

There have been several attempts to assess patterns of fish passage based on species-specific utilization (i.e. relative usage rates, seasonal and thermal usage patterns, time of day, duration of passage) as well as hydraulic conditions during use by trapping fish within a fish passage structure (Oldani and Baigun, 2002; O'Connor *et al*., 2003; Pratt *et al*., 2006) or by marking and recapturing fish along their migration route (Linløkken, 1993; O'Connor *et al*., 2003; Knaepkens *et al*., 2006). Data obtained from these studies provide some useful but limited information related to efficiency of fish attraction and fish passage at dams, weirs and other barriers to fish migration. Efficiency of fish movement at an area of difficult passage involves knowing how

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many fish of a particular species attempt to pass upstream relative to the number of fish that successfully pass through (Bunt, 1999; Bunt *et al*., 1999; Larinier *et al*., 2005; Castro-Santos and Haro, 2010; Roscoe and Hinch, 2010). Quantitative evaluation of the factors affecting fish attraction and passage requires detailed information on the movement patterns of individually identifiable fish. This is best accomplished using telemetry.

Some of the terminology for fish passage structures has not been formally established and defined. Therefore, the following terms are herein used to clarify any confusion related to nomenclature for describing various fish passage structures: In this paper, a fish passage structure is any structure built to facilitate the upstream passage of fish through a riverine environment. Technical fishways incorporate artificial flow reduction elements such as baffles (e.g. Denil and Alaska steeppass—hereafter grouped as Denil fishways) or steps (e.g. pool-and-weir, vertical-slot fishways), whereas nature-like fishways contain natural features that increase bottom roughness such as cobble and boulders, although they may incorporate some engineered elements such as anchored concrete blocks or other artificial elements that may be found in technical fishways. Fish locks and fish lifts use mechanical locking gates to direct fish and lifting devices such as baskets to physically move them past barriers. In the context of this study, a fishway is any type of riverine channel segment created to passively facilitate fish migration across an elevated barrier without any direct human or mechanical intervention.

The objective of this paper is to quantify, summarize, compare and review the upstream attraction and passage efficiencies for various species of anadromous and potamodromous fish through fishways using data from studies with comparable attributes. These data were derived from peer-reviewed, published scientific studies and consultant reports, in which individual fish were tracked and attraction and passage efficiencies were calculated. Data were then mathematically analysed using principal components analysis (PCA) and multiple logistic regression to determine what factors affected fish attraction and passage.

METHODS

Data from peer-reviewed scientific studies, agency and consultant reports and other grey-literature were systematically collected and summarized in a matrix (Appendix A). Each of these studies contained data on fish attraction and/or passage efficiency following a specific methodology in which fish were tracked as they approached and attempted to pass upstream through fishways under natural conditions (i.e. field-based rather than laboratory-derived observations). Fish positions were detected at the entrances and exits of most structures to quantify attraction and confirm successful passage. Attraction efficiency was defined as the proportion of fish tagged and released during the study that were subsequently located within less than approximately 3 m from a fishway entrance (Bunt *et al*., 1999) or at the base of a barrier to fish movement and near enough to a fishway entrance for fish to detect fishway attraction flow (Aarestrup *et al*., 2003). In most cases, existing data were not sufficient for testing actual rates at which fish entered the structures (Castro-Santos *et al*., 2009; Castro-Santos and Haro, 2010) or potential delay. Passage efficiency was calculated by dividing the number of fish of a particular species that exited a fishway by the number that was detected at the fishway entrance (Bunt *et al*., 1999; Aarestrup *et al*., 2003).

To standardize values and minimize confounding variables, studies were considered appropriate for inclusion in this meta-analysis if they:

(1) Included data from fish that were individually monitored using radio, acoustic or PIT (passive integrated transponder) telemetry as follows: (i) to detect the number of fish at or near the entrance of each structure to accurately quantify attraction efficiency; and (ii) to determine the number of fish that successfully passed through and exited the structure to accurately quantify passage efficiency.
(2) Provided data from anadromous/potamodromous fish actively migrating upstream in rivers (usually before the spawning period) during a single spawning season. This minimizes effects of losses through death, emigration and tag failure. Data from multi-year studies, multiple species and studies from multiple sites and/or multiple fishways were separated accordingly.
(3) Were based on evaluations of fish behaviour under natural conditions. In order to accurately quantify attraction and passage efficiency, individual fish had to approach and ascend each structure without any form of artificial intervention, such as being corralled in chambers or coerced by physical prodding, electric shock, strobe lights or other means.

Mark–recapture studies (e.g. Oldani and Baigun, 2002; Knaepkens *et al*., 2006) were rejected from the analysis because individual fish were not tracked. Further examples of studies with data that appeared suitable for this study, but were subsequently rejected from the meta-analysis, involved the tracking of the upstream movement of individually tagged bony herring (*Nematalosa erebi*) in an Australian Denil fishway (Mallen-Cooper and Stuart, 2007) and American shad and blueback herring through a Denil/Alaska steeppass fishway in a laboratory flume (Haro *et al*., 1999). Individual fish in these studies did not naturally locate and ascend the fishways and were corralled into a staging area near the fishway entrance and then released, violating criterion #3. Studies of lift/lock structures were

DOI: 10.1002/rra

also excluded from this review for the same reason, as these structures use mechanical gates, elevators and baskets to manoeuver and lift fish over migration barriers. Anguilliform ladders are designed for passage of catadromous species violating criterion #2. However, early life-stage eels are upstream migrants that are inhibited by barriers to migration, but eel ladders are extremely family-specific and do not allow for cross-family comparisons.

To determine the influence of biological factors (i.e. morphology or life-history) on fishway performance, fish were grouped by the following categorical variables: species, family, general habitat type (warm/cool-water), fin ray type (soft/spiny) and migration tendency (anadromous/potamodromous). Continuous fishway structure variables such as slope and change in elevation (ΔE) were extracted from each study, as were categorical data (location, structure type, design characteristics, monitoring methodology) for each of the fishways studied. Four types of fishways were analysed separately and more broadly as being technical (i.e. pool-and-weir, vertical-slot and Denil) or nature-like in design. Because each variable was non-uniformly distributed with respect to fishway type, the data matrix could not be analysed using standard regression methods because of assumed independence among covariates. To control for this effect, PCA was performed on the dataset and logistic regression was used to evaluate the effects of the components on fish attraction and passage performance. Statistical tests were conducted using the PRINCOMP procedure for principle components analysis and the PROC LOGISTIC procedure for logistic regression with SAS version 9.2 (SAS Institute Inc., Cary, NY, USA). The Scale=Pearson function was used to control for over-dispersion in the data. Logistic regression output was subsequently coded by morphology (specifically fin ray type), migratory mode (anadromy and potamodromy) and general habitat (warm water/cool water systems)—see Table I. Engineered variables analysed were fishway type, ΔE and slope.

RESULTS

From 116 available peer-reviewed scientific papers and consultant reports, only 19 satisfied the three criteria for this analysis and described upstream passage performance at 35 distinct fishways at 28 locations. When separated by year and species, there were 101 records of data, from 26 species

Table I. Taxonomic family, general habitat type, fin ray type and migration tendencies of all species included in the principal components analysis and logistic regression analysis

Family	Species	Habitat type	Fin ray type	Migration tendency
Catostomidae	White sucker (*Catostomus commersoni*)	Warm water	Soft	Anadromous
Centrarchidae	Rock bass (*Ambloplites rupestris*)	Warm water	Spiny	Potamodromous
	Smallmouth bass (*Micropterus dolomieu*)	Warm water	Spiny	Potamodromous
Clupeidae	Alewife (*Alosa pseudoharengus*)	Warm water	Soft	Anadromous
	American shad (*Alosa sapidissima*)	Warm water	Soft	Anadromous
Cyprinidae	Baltic vimba (*Vimba vimba*)	Warm water	Soft	Potamodromous
	Chub (*Leuciscus cephalus*)	Warm water	Soft	Potamodromous
	Common bream (*Abramis brama*)	Warm water	Soft	Potamodromous
	Common shiner (*Notropis cornutus*)	Warm water	Soft	Potamodromous
	Creek chub (*Semotilus atromaculatus*)	Warm water	Soft	Potamodromous
	Roach (*Rutilus rutilus*)	Warm water	Soft	Potamodromous
	Rudd (*Scaridinus erythropthalmus*)	Warm water	Soft	Potamodromous
	Tench (*Tinca tinca*)	Warm water	Soft	Potamodromous
Esocidae	Northern pike (*Esox lucius*)	Warm water	Soft	Potamodromous
Ictaluridae	Brown bullhead (*Ameiurus nebulosus*)	Warm water	Soft	Potamodromous
Lotidae	Burbot (*Lota lota*)	Warm water	Soft	Potamodromous
Moronidae	Striped bass (*Morone saxatilis*)	Warm water	Spiny	Anadromous
Percidae	Perch (*Perca fluviatilis*)	Warm water	Spiny	Potamodromous
	Walleye (*Sander vitreus vitreus*)	Warm water	Spiny	Potamodromous
	Zander (*Sander lucioperca*)	Warm water	Spiny	Potamodromous
Salmonidae	Atlantic salmon (*Salmo salar*)	Cool water	Soft	Anadromous
	Brown trout (*Salmo trutta*)	Cool water	Soft	Anadromous[a]
	Chinook salmon (*Oncorhynchus tshawytscha*)	Cool water	Soft	Anadromous
	Pink Salmon (*Oncorhynchus gorbuscha*)	Cool water	Soft	Anadromous
	Rainbow trout (*Oncorhynchus mykiss*)	Cool water	Soft	Anadromous
	Sockeye salmon (*Oncorhynchus nerka*)	Cool water	Soft	Anadromous

[a]Although some populations are potamodromous, all species included in this review were anadromous.

DOI: 10.1002/rra

of fish in six countries—Canada, Denmark, Russia, Scotland, Sweden and the United States (Figure 1, Table II), and four categories of fishway structures: pool-and-weir, Denil, vertical-slot and nature-like bypass channels. No data were available from the Southern hemisphere. Fourteen evaluations focused on salmonids and clupeids, yielding 63 records of data when separated by year, fishway type and species (Appendix A). There was an asymmetrical balance within our data matrix and there were insufficient numbers of fish passage studies by non-salmonid/clupeid species at fishways with $\Delta E > 12$ m (for an exception, see Parsley *et al.*, 2007) and vice versa.

Attraction and passage performance

Box and whisker plots showed that attraction efficiency varied broadly across all fishway types [Figure 2(a)]. Pool-and-weir (range=29–100%, mean=77%, median=81%), vertical-slot (range=0–100%, mean=63%, median=80%) and Denil (range=21–100%, mean=61%, median=57%) type fishways were broadly comparable, but attraction into nature-like fishways (range=0–100%, mean=48%, median=50%) was notably worse than in technical types. Passage efficiency also varied broadly across all fishway types [Figure 2(b)]. Ranges and mean values were 0–100% (mean=40%, median=34%) for pool-and-weir fishways, 0–100% (mean=45%, median=43%) for vertical-slot fishways, 0–97% (mean=51%, median=38%) for Denil fishways and 0–100% (mean=70%, median=86%) for nature-like fishways. In contrast to attraction, nature-like fishways performed better, generally passing more fish of more species than the technical types (Figure 2, Table II).

Principal components analysis

Principal components analysis of morphology, migratory mode, general habitat and fishway groupings, showed that the first four principal components (PC1, PC2, PC3 and PC4) contributed substantially to the overall variance and were therefore included in the logistic regression analysis. For passage analysis, both slope and ΔE were added to the PCA, producing six components. The first four components cumulatively explained 100% of the variability in fish attraction and 89% of the variability in passage and were therefore deemed sufficient for inclusion in the analysis.

Figure 1. Locations of rivers and streams where fish passage monitoring and assessment studies have been conducted using methodology that provided data appropriate for this meta-analysis (indicated by dots).

Table II. Summary of meta-analysis data from 101 evaluations involving 19 studies that examined movement of 26 fish species at instream barriers to fish migration

Structure type	*n* evaluations	Slope (%)	ΔE (m)	Mean attraction (%)	Mean passage (%)	Pooled attraction (%)	Pooled passage (%)	Total efficiency (%)	*n* entering	*n* exiting	*n* fish
Pool-and-weir	44	7.0	15.13	77	40	77	56	43	8695	4881	11,268
Vertical-slot	29	10.7	1.81	63	45	88	50	44	3162	1578	3587
Denil	7	15.7	2.03	61	51	81	77	62	349	269	431
Nature-like	21	3.0	6.33	48	70	56	76	43	641	488	1151
Total	101	7.8	18.26	66	48	78	56	44	12,847	7216	16,437

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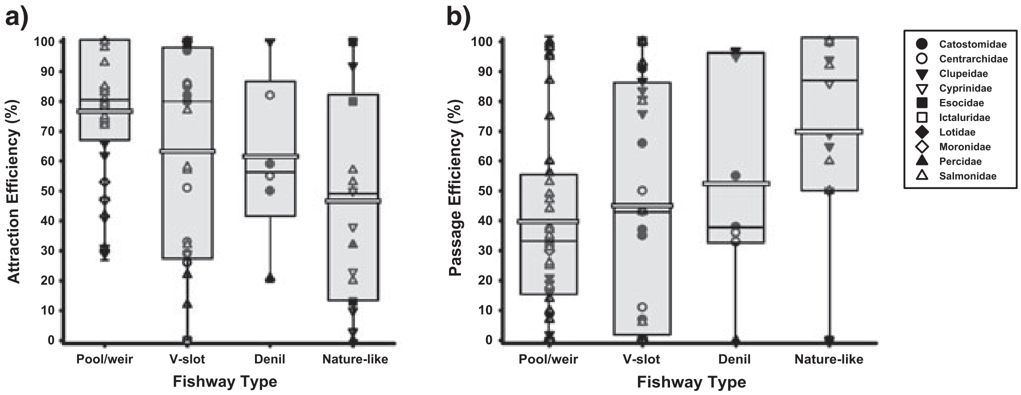

Figure 2. Box and whisker plots for each fishway type, arranged on the *x*-axis from greatest to least attraction efficiency (a) and least to greatest passage efficiency (b), summarizing maximum, minimum, median (black line) mean (white line) and outlier values

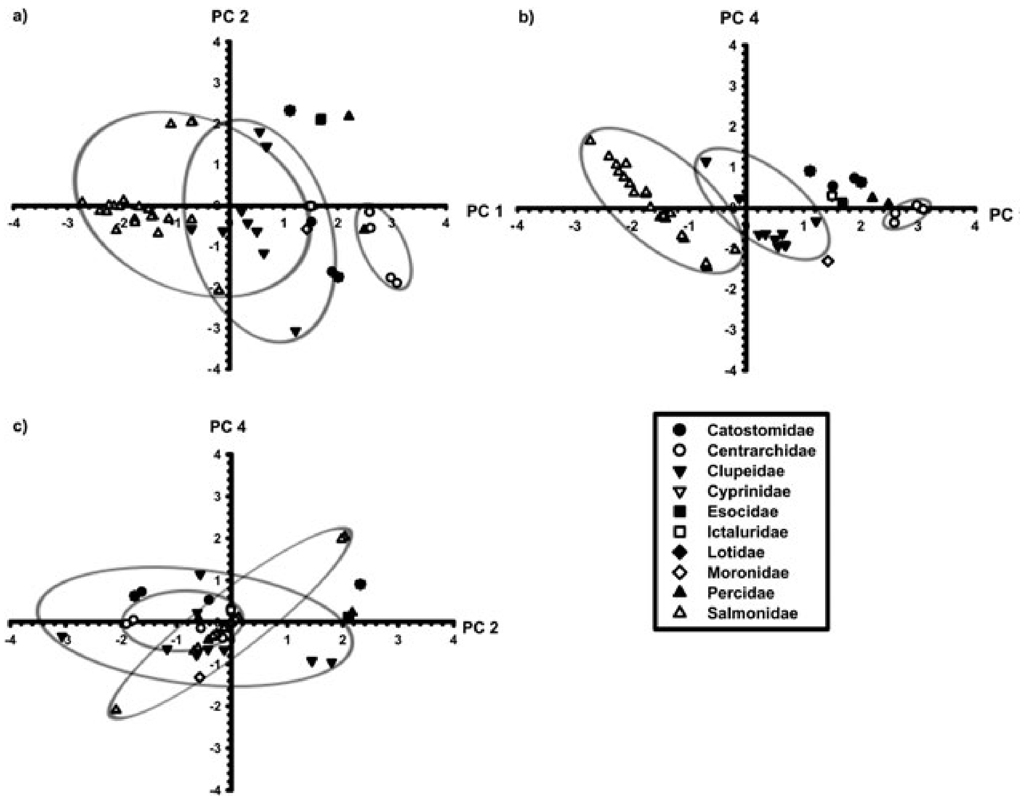

Figure 3. PC1 (principal component 1) versus PC2 (principal component 2) (a), PC1 versus PC4 (principal component 4) (b) and PC2 versus PC4 (c) for passage and coded taxonomically by family

Graphical representations of the PCA showed interesting relationships and data separation—some of which were statistically significant and others that were not. Figure 3 shows that anadromous species clustered to the centre and to the left of PC1, with salmonids occupying the most negative positions and centrarchids and percids (both spiny-rayed families) separated in the right-most positions. Salmonids weighed negatively on PC1 but were distributed approximately evenly with respect to PC2. Clupeids and salmonids were fairly clustered, likely correlated with the fact that anadromous/potamodromous species were an important influence on PC1, as all clupeids and salmonids that were studied were anadromous. This plot also indicates separation between anadromy and barrier height. PC2 was associated with fishway type and slope. Nature-like structures separated from technical fishways with positive values associated with

DOI: 10.1002/rra

nature-like fishways and low slopes (Figure 4). Spiny-rayed fishes loaded negatively on PC2, but had their strongest effect on PC3, where they were associated with positive values. PC4 was mostly influenced by anadromy, with positive loading and similar magnitude as PC1, and by warm-water versus cool-water habitat, where the sign was opposite of PC1 (negative loading on PC1, positive loading on PC4).

Attraction

Slope and ΔE were omitted from the analysis of attraction efficiency. These variables were assumed to not influence attraction to the fishway entrance, which is mostly affected by entrance location, near-field hydraulic conditions and entrance configuration. Values in the upper portion of Table III are eigenvectors, representing the effect of a linear combination of the variables on each principal component. Positive values indicate a positive correlation with the principal component, negative values indicate a negative correlation, and the magnitude or eigenvalue (bottom of Table III) reflects the scale of the relationship and corresponds to the total variance explained by each principal component. Maximum likelihood estimates of the regression coefficients and associated probabilities (Table III) showed that PC3 and

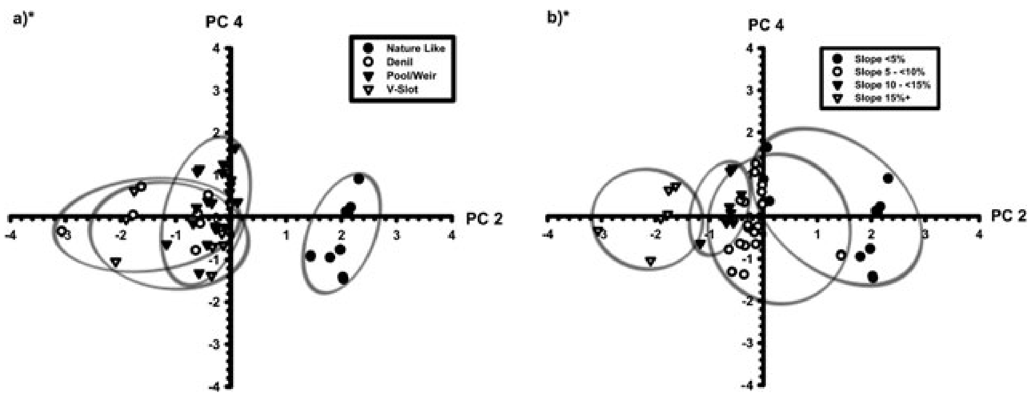

Figure 4. PC2 (principal component 2) versus PC4 (principal component 4), for passage coded by fishway type (a) and slope (b). Note the separation of nature-like fishways in (b) demonstrating the strong influence of technical/nature-like fishways on PC2 (* indicates statistical significance). Each slope interval in (b) spans different fishway types (a) and runs almost parallel to PC2, demonstrating its strong influence on overall variability

Table III. Summary of principal components and logistic regression analysis of attraction efficiency and passage efficiency

	Attraction				Passage			
Attribute	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
Soft-rayed/spiny-rayed	0.432	−0.536	0.718	−0.099	0.355	−0.479	0.867	−0.218
Anadromous/potamodromous	0.623	0.042	−0.241	0.743	0.529	0.127	0.010	0.533
Warm/cool water	−0.602	0.009	0.459	0.653	−0.546	−0.035	0.133	−0.275
Technical/nature-like	0.251	0.843	0.464	−0.107	0.130	0.723	−0.226	−0.067
Slope	–	–	–	–	0.209	−0.675	−0.288	0.109
Height (ΔE)	–	–	–	–	−0.485	0.045	0.311	0.760
Principal components analysis								
Eigenvalue	2.012	1.034	0.627	0.327	2.496	1.486	0.843	0.522
Proportional variance	0.503	0.259	0.157	0.082	0.416	0.248	0.140	0.087
Cumulative variance	0.503	0.762	0.918	1.000	0.416	0.664	0.804	0.891
Logistic regression analysis								
Coefficient	−0.232	−0.197	−0.700	0.828	−0.144	0.731	−0.093	0.535
$p >$ chi square (Wald)	0.063	0.305	0.001	0.0001	0.400	0.004	0.835	0.061

Attribute values are eigenvectors with negative values correlated with reduced attraction/passage and positive values correlated with increased attraction/passage. The first four attributes are dichotomous variables that were coded for the principal components analysis with the term on the left being assigned 0 and the term on the right being assigned a value of 1 (e.g. for soft-rayed/spiny-rayed, soft-rayed =0 and spiny-rayed =1).
PC1, principal component 1; PC2, principal component 2; PC3, principal component 3; PC4, principal component 4.

DOI: 10.1002/rra

PC4 were statistically significant. PC1 was considered marginally insignificant and PC2 was insignificant. Eigenvectors indicated that PC1 was driven by biological characteristics of the fish that were studied (i.e. whether they were anadromous or potamadromous or whether they were adapted to warm-water or cool-water environments). PC2 was insignificant and was driven largely by variation related to technical versus nature-like fishways. PC3 was influenced predominantly by fin ray characteristics and PC4 was mostly related to the same driving factors as PC1 (anadromous/potamadromous and warm-water/cool-water species). Patterns of attraction appear to be driven by the biological characteristics of the fish that were studied, suggesting that attraction to fishways may have more to do with fish behaviour and biology rather than structure type or hydraulics. However, there was some ambiguous evidence to support poorer attraction among nature-like fishways compared with technical fishways (negative coefficients for PC1–3 and positive coefficient for PC4, Table III).

Passage

With all four principal components included in the analysis, the only component that was significant was PC2 (p=0.004, Table III). PC2 indicated that nature-like and lower slope fishways had higher passage efficiencies. Principal component 2 was driven by general fishway design characteristics and slope (technical versus nature-like with positive values for nature-like fishways and low slopes, Figure 4, Table III). Note that slope had a negative eigenvector loading (−0.67). PC4 was marginally insignificant (p=0.06) but became significant (p=0.02) when PC1 and PC3 (driven by fin ray type) were removed from the analysis. PC4 was largely driven by ΔE (positive groupings, Figure 5, Table III) and was related to the effects of studies on salmonids and clupeids at large dams—as suggested by moderately high anadromous loadings (0.53) on PC4.

The non-significance of the third principal component is interesting in that it was strongly influenced by whether study species had soft or spiny fin rays. Non-significance of this factor suggests that this may not be a strong determinant in fish passage.

DISCUSSION

Available data do not clearly justify recommendations for any particular fishway type. Although there was some suggestion that nature-like fishways have better passage performance, it

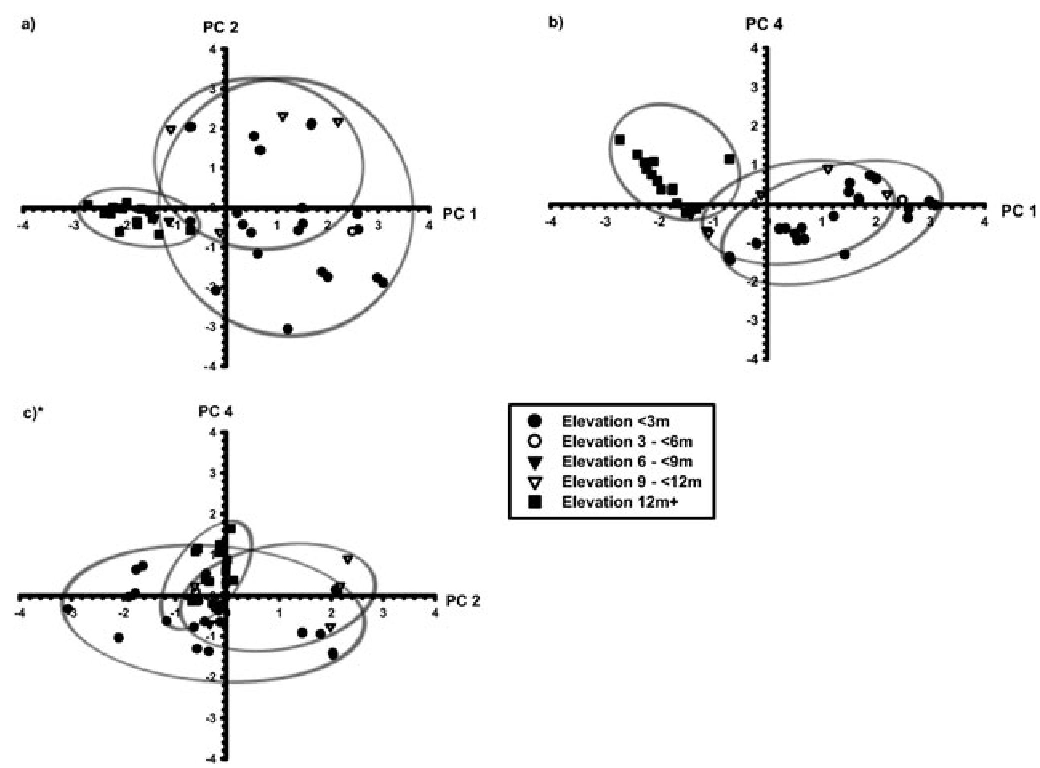

Figure 5. Passage analysis of PC1 (principal component 1) versus PC2 (principal component 2) (a), PC1 versus PC4 (principal component 4) (b) and PC2 versus PC4 (c) coded by fishway height or ΔE (* indicates statistical significance). Fishways with ΔE greater than 12 m are often pool-and-weir fishways and are tightly clustered in both plots, indicating a strong influence of ΔE on PC4

DOI: 10.1002/rra

is important to recognize that nature-like fishways tend to be built with very low slope, and it is possible that the superior passage performance of this fishway type is largely attributable to slope rather than to any other intrinsic benefit of their design. Nature-like fishways appear to function well for species with reduced swimming performance (Bunt, 2006; Calles and Greenberg, 2007), but there were many cases when flow was too low to effectively attract fish to the entrance location (Moser *et al*., 2000; Larinier *et al*., 2005; Sprankle, 2005). More work is needed on the design of nature-like fishways before they can be reliably prescribed, as they often are, for passing a broad variety of species.

Our analysis suggests that the most important biological factors that drive attraction efficiency and passage efficiency are migratory characteristics (i.e. if the monitored species was anadromous or potamodromous) and thermal tolerance (i.e. if the species was considered to be adapted to warm-water or cool-water conditions, Table II). This finding is consistent with the fact that high performing salmonids and clupeids in the studies analysed were anadromous and adapted to cool water, whereas all other species were potamodromous and considered warm-water tolerant. Salmonids are generally strong swimmers and can be passed upstream through a wide array of fishways, with close to 100% passage efficiency in some structures (Gowans *et al*., 1999; O'Connor *et al*., 2003; Calles and Greenberg, 2005; Naughton *et al*., 2005; Pon *et al*., 2006; Roscoe and Hinch, 2008).

There was some suggestion that pool-and-weir and vertical-slot fishways generally had better attraction than Denil and nature-like fishways. This relationship can likely be attributed to differences in the amount of attraction flow provided by each fishway type (Pratt *et al*., 2006; Naughton *et al*., 2007). Migrating fish tend to be drawn to areas of higher flow, leading to higher attraction efficiency to pool-and-weir and vertical-slot fishways. These fishways are often large structures and vertical-slot fishways typically track river discharge; however, both types tend to have reduced passage efficiency relative to other designs (Karppinen *et al*., 2002; Mallen-Cooper and Brand, 2007; Peake, 2008). The results and interpretations of these analyses are based on studies in temperate rivers in the northern hemisphere and may not apply in the tropics, where higher metabolic rates may correspond to superior performance (Santos *et al*., 2007). Although not clearly shown in this analysis, there is evidence to suggest that soft-rayed fishes may out-perform spiny-rayed fishes in turbulent or unstable flow conditions (Webb, 1998). Therefore, rivers with greater biodiversity require fish passage solutions that can accommodate species with a wide range of sizes, swimming abilities (Schmutz *et al*., 1998; Webb, 1998; Mallen-Cooper and Stuart, 2007) and other upstream migration strategies. The swimming abilities of fish are but one of the many factors that must be considered when attempting to improve fish passage, even though accounting for all aspects of swimming ability is difficult to quantify objectively. Physiological, behavioural and motivational factors are similarly difficult to measure and are beyond the scope of this review; however, it is important to note that they all probably have a substantial influence on attraction and passage efficiency. Fishway facilities produce hydraulic features not found in nature and may therefore depress passage (Knaepkens *et al*., 2006; Castro-Santos *et al*., 2009).

It appears that many fishways have entrances that are poorly located (Larinier *et al*., 2005) or produce flows that are insufficient to attract fish away from other areas with higher, distracting discharge (Bunt *et al*., 1999; Gowans *et al*., 1999; Bunt, 2001; Oldani and Baigun, 2002; Sprankle, 2005). Excessive turbulence (Barry and Kynard, 1986; Haro and Kynard, 1997; Lucas *et al*., 1999; Bunt *et al*., 2000; McGrath *et al*. 2003; Sprankle, 2005; Mallen-Cooper and Brand, 2007) and extreme water velocities (Haro and Kynard, 1997; Knaepkens *et al*., 2006; Mallen-Cooper and Brand, 2007) have been interpreted as factors that challenge many sizes and species of upstream migrating fish in fishway structures.

Interpreting available fish passage data is complicated by the fact that important covariates are not equally distributed among fishway types. No data will likely ever be collected from nature-like fishways with extreme ΔE (greater than 12 m) and a slope greater than 15%. Nature-like designs are often an impractical solution for overcoming such obstacles and are not usually designed to operate at sites with such ΔE differentials. Similarly, there were insufficient data related to vertical-slot or pool-and-weir fishways with slope gradients $<5\%$. Based on these limitations, this analysis should be approached with caution, as certain ΔE and slopes are common to specific fishway designs and impractical for other types across a wide range of ΔE and slopes.

The vast majority of fishway structures do not effectively mitigate the effects of barriers that block access to areas upstream. Several researchers reported fish abandoning upstream movement part way through a passage structure and repeated unsuccessful attempts to use different fishways (Haro and Kynard, 1997; Bunt *et al*., 1999; Aarestrup *et al*., 2003; Parsley *et al*., 2007). In most cases, fish attracted to a fishway entrance are assumed to have responded to fishway attraction flows, but this does not necessarily imply that these fish actually entered the fishway. Modifications and improvements to existing and new fishways will be enhanced if monitoring projects are designed to examine each of these components and quantify them as proportions per unit time [i.e. attraction should include at least two sub-components—arrival at the entrance (guidance) and the decision to enter (entry), as well as exit (passage)]. This will allow managers and researchers to decouple the relative

DOI: 10.1002/rra

contribution of each component and to identify the cause of passage problems where they exist. Failure to consistently quantify each of these components introduced error into our analysis. In some cases, we were only able to determine whether fish approached fishway entrances but not whether they actually entered the structure. We were therefore unable to consistently determine whether poor passage resulted from a rejection of the fishway entrances or the hydraulic/structural conditions within the fishways themselves. These and similar uncertainties will remain until standardized evaluation methods are adopted.

In conjunction with standardized fishway evaluations, new fishway modifications and designs that incorporate a number of hybrid components of certain fishway types should be tested to improve attraction and passage rates. For example, fishway designs with a properly located narrow technical entrance, and a more nature-like design towards its exit, may produce the necessary flow to attract fish while allowing passage with minimal energy expenditure. Similarly, nature-like fishways may be designed with the addition of supplemental attraction flows. Several attempts to improve fish attraction and passage performance by altering sections of fishways have already been undertaken with some success. One experiment at the Baigts hydroelectric dam on the Gave de Pau River in France indicated that the passage efficiency of Atlantic Salmon (*Salmo salar*) was improved significantly by increasing flow at the entrance of the Denil fishway (Larinier *et al*., 2005). The research team in this case improved fish passage by enhancing fish attraction, not modifying hydraulic conditions inside the fishway. Another study at a pool-and-weir fishway in Scotland involved screening off a dam tailrace to prevent fish from accessing competing attraction flows from turbine discharge (Gowans *et al*., 1999). Researchers were also able to increase attraction efficiency of two Denil fishways in the Grand River, Ontario by enlarging and slightly relocating the fishway entrances (Bunt, 2001). Because of minimal cost, and obvious benefits, more studies on the effectiveness of altering fishways in relation to entrance shape and location, discharge, entrance flow augmentation and the blocking of competing flows should be considered.

Summary

Fish migration in rivers continues to command attention from a diverse group of agencies, conservation biologists and special interest groups; however, there is still a long way to go before issues related to fish passage are fully resolved. Given the paucity of suitable data and the high degree of variability in existing data, it is premature to propose guidelines for structure design. Instead, we encourage managers to require evaluations as part of fishway construction, and to adopt standardized methods for performing those evaluations that will allow for better comparisons of attraction, and passage, as well as identification of conditions that optimize each component. Schmutz *et al*. (1998) noted that despite the great number of fishways and other fish passage structures constructed around the world, very few have been evaluated. Continued and standardized monitoring of fish passage will contribute to a valuable database from which successful fish passage designs and construction decisions can be made.

ACKNOWLEDGEMENTS

Financial support for this project was provided by Biotactic Fish and Wildlife Research Incorporated, ECO Canada (Environmental Careers Organization Canada) and the Industrial Research Assistance Program administered by the National Research Council of Canada. The authors wish to thank all of the researchers who were contacted and contributed data for this project. We are also grateful to Stephanie Choo-Wing, Jeanette O'Hara-Hines (University of Waterloo Department of Statistics and Actuarial Science) and Emily Taylor for research and assistance with data analysis, figure designs and manuscript preparation.

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APPENDIX A. SUMMARY OF STUDIES THAT FOLLOWED A STANDARDIZED FISH MONITORING PROTOCOL AND YIELDED DATA USEFUL FOR THIS META-ANALYSIS

Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
Town Brook (Billington St. Fishway 2006)—Plymouth, MA	Pool-and-weir	Pool-and-weir fishway, 14-m long	14.00	0.91	0.91	PIT tag	29	21	6	28	6	96	Alewife (*Alosa pseudoharengus*)	Franklin (2009)
Connecticut R. (Spillway 1999)—MA, USA	Pool-and-weir	Modified Ice Harbor with 35 pools, 180-m long	5.90	10.67	10.67	PIT tag	84	17	14	42	7	50	American shad (*Alosa sapidissima*)	Sullivan (2004)
Connecticut R. (Spillway 2000)—MA, USA	Pool-and-weir	Modified Ice Harbor with 35 pools, 180-m long	5.90	10.67	10.67	PIT tag	31	8	3	73	6	235	American shad (*Alosa sapidissima*)	Sullivan (2004)
Connecticut R.—(Cabot 1999) MA, USA	Pool-and-weir	Modified Ice Harbor with 66 pools, 264-m long	7.60	20.11	20.11	PIT tag	66	19	13	99	19	150	American shad (*Alosa sapidissima*)	Sullivan (2004)
Connecticut R.—(Cabot 2001) MA, USA	Pool-and-weir	Modified Ice Harbor with 66 pools, 264-m long	7.60	20.11	20.11	PIT tag	41	16	7	140	22	345	American shad (*Alosa sapidissima*)	Sullivan (2004)
Connecticut R.—(Cabot 2002) MA, USA	Pool-and-weir	Modified Ice Harbor with 66 pools, 264-m long	7.60	20.11	20.11	PIT tag	47	2	1	152	3	326	American shad (*Alosa sapidissima*)	Sullivan (2004)
Connecticut R.—(Cabot 2000) MA, USA	Pool-and-weir	Modified Ice Harbor with 66 pools, 264-m long	7.60	20.11	20.11	PIT tag	62	17	11	154	27	250	American shad (*Alosa sapidissima*)	Sullivan (2004)
Neuse R.—(Quaker Neck Dam 1997) NC, USA	Pool-and-weir	25.3-m long, submerged orifice, poor attraction flows, decommissioned in 1998	8.00	2.03	2.03	Radio telemetry	29	0	0	4	0	14	American shad (*Alosa sapidissima*)	Beasley and Hightower (2000)
Neuse R.—(Quaker	Pool-and-weir	25.3-m long, submerged	8.00	2.03	2.03	Radio telemetry	100	0	0	12	0	12		Beasley and

DOI: 10.1002/rra

APPENDIX A
(Continued)

Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
Neck Dam 1996) NC, USA		orifice, poor attraction flows, decommissioned in 1998											American shad (*Alosa sapidissima*)	Hightower (2000)
Kola Fijord (Lower Tuloma 2000)—Russia	Pool-and-weir	66 pools with a length of 513 m	3.70	19.00	19.00	Radio telemetry	31	75	23	4	3	13	Atlantic salmon (*Salmo salar*)	Karppinen *et al.* (2002)
R. Tummel (Pitlochry D. 1995)—Scotland	Pool-and-weir	Fish ladder, 310-m long, 34 chambers, 180 hairpin turn	4.80	20.00	15.00	Radio telemetry	74	100	74	29	29	39	Atlantic salmon (*Salmo salar*)	Gowans *et al.* (1999)
(Stornorrfors D. 1995) Umeälven, Sweden	Pool-and-weir	240-m-long channel with 65 pools and weirs	7.50	18.00	18.00	Radio telemetry	73	0	0	22	0	30	Atlantic salmon (*Salmo salar*)	Lundqvist *et al.* (2008)
(Stornorrfors D. 1999) Umeälven, Sweden	Pool-and-weir	240-m-long channel with 65 pools and weirs	7.50	18.00	18.00	Radio telemetry	83	34	28	50	17	60	Atlantic salmon (*Salmo salar*)	Lundqvist *et al.* (2008)
(Stornorrfors D. 2001) Umeälven, Sweden	Pool-and-weir	240-m-long channel with 65 pools and weirs	7.50	18.00	18.00	Radio telemetry	79	18	14	55	10	70	Atlantic salmon (*Salmo salar*)	Lundqvist *et al.* (2008)
(Stornorrfors D. 1997) Umeälven, Sweden	Pool-and-weir	240-m-long channel with 65 pools and weirs	7.50	18.00	18.00	Radio telemetry	84	26	22	67	17	80	Atlantic salmon (*Salmo salar*)	Lundqvist *et al.* (2008)
(Stornorrfors D. 2003) Umeälven, Sweden	Pool-and-weir	240-m-long channel with 65 pools and weirs	7.50	18.00	18.00	PIT tag/ Radio telemetry	83	35	29	325	114	391	Atlantic salmon (*Salmo salar*)	Lundqvist *et al.* 2008
(Stornorrfors D. 2005) Umeälven, Sweden	Pool-and-weir	240-m-long channel with 65 pools and weirs	7.50	18.00	18.00	PIT tag/ Radio telemetry	80	47	38	360	169	450	Atlantic salmon (*Salmo salar*)	Lundqvist *et al.* (2008)
(Stornorrfors D. 2002) Umeälven, Sweden	Pool-and-weir	240-m-long channel with 65 pools and weirs	7.50	18.00	18.00	PIT tag/ Radio telemetry	78	47	37	385	181	493	Atlantic salmon (*Salmo salar*)	Lundqvist *et al.* (2008)
(Stornorrfors D. 2004) Umeälven, Sweden	Pool-and-weir	240-m-long channel with 65 pools and weirs	7.50	18.00	18.00	PIT tag/ Radio telemetry	93	14	13	468	66	503	Atlantic salmon (*Salmo salar*)	Lundqvist *et al.* (2008)
Snake R. (Lower Granite Dam 2002)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool	6.60	77.40	11.90	Radio telemetry	100	0	0	7	0	7	Chinook salmon (*Oncorhynchus tshawytscha*)	Naughton *et al.* (2007)

DOI: 10.1002/rra

APPENDIX A
(Continued)

Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
		for evaluation (control), 1:10 and 1:32 slopes												
Snake R. (Lower Granite Dam 2001)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for evaluation (control), 1:10 and 1:32 slopes	6.60	77.40	11.90	Radio telemetry	100	33	33	18	6	18	Chinook salmon (*Oncorhynchus tshawytscha*)	Naughton *et al.* (2007)
Snake R. (Lower Granite Dam 2002)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for evaluation (treatment—flow restricted), 1:10 and 1:32	6.60	77.40	11.90	Radio telemetry	100	25	25	24	6	24	Chinook salmon (*Oncorhynchus tshawytscha*)	Naughton *et al.* (2007)
Snake R. (Lower Granite Dam 2001)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for evaluation (treatment—flow restricted), 1:10 and 1:32	6.60	77.40	11.90	Radio telemetry	100	38	38	37	14	37	Chinook salmon (*Oncorhynchus tshawytscha*)	Naughton *et al.* (2007)
Snake R. (Lower Granite Dam 2002)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for evaluation (control), 1:10 and 1:32 slopes	6.60	77.40	11.90	Radio telemetry	100	37	37	114	42	114	Chinook salmon (*Oncorhynchus tshawytscha*)	Naughton *et al.* (2007)
Snake R. (Lower Granite Dam 2002)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for evaluation (treatment—flow restricted), 1:10 and 1:32	6.60	77.40	11.90	Radio telemetry	100	53	53	146	78	146	Chinook salmon (*Oncorhynchus tshawytscha*)	Naughton *et al.* (2007)

APPENDIX A
(Continued)

Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
Snake R. (Lower Granite Dam 2001)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for evaluation (treatment—flow restricted), 1:10 and 1:32	6.60	77.40	11.90	Radio telemetry	100	37	37	208	76	208	Chinook salmon (*Oncorhynchus tshawytscha*)	Naughton *et al.* (2007)
Snake R. (Lower Granite Dam 2001)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for evaluation (control), 1:10 and 1:32 slopes	6.60	77.40	11.90	Radio telemetry	100	10	10	209	21	209	Chinook salmon (*Oncorhynchus tshawytscha*)	Naughton *et al.* (2007)
Snake R. (Lower Granite Dam 2001)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for evaluation (control), 1:10 and 1:32 slopes	6.60	77.40	11.90	Radio telemetry	100	49	49	80	39	80	Rainbow trout (*Oncorhynchus mykiss*)	Naughton *et al.* (2007)
Snake R. (Lower Granite Dam 2001)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for evaluation (treatment—flow restricted), 1:10 and 1:32	6.60	77.40	11.90	Radio telemetry	100	49	49	93	46	93	Rainbow trout (*Oncorhynchus mykiss*)	Naughton *et al.* (2007)
Snake R. (Lower Granite Dam 2002)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for evaluation (control), 1:10 and 1:32 slopes	6.60	77.40	11.90	Radio telemetry	100	32	32	170	55	170	Rainbow trout (*Oncorhynchus mykiss*)	Naughton *et al.* (2007)
Snake R. (Lower Granite Dam 2002)—WA, USA	Pool-and-weir	Three entrances lead to collection channel, then transition pool for	6.60	77.40	11.90	Radio telemetry	100	44	44	174	77	174	Rainbow trout (*Oncorhynchus mykiss*)	Naughton *et al.* (2007)

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APPENDIX A
(Continued)

Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
		evaluation (treatment—flow restricted), 1:10 and 1:32												
Columbia R. (John Day 1997)—OR and WA, USA	Pool-and-weir	Two fishways, 1:16 slope at weir entrance, 1:32 slope at flow control	4.70	32.00	32.00	Radio telemetry	85	95	81	492	468	577	Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Columbia R. (Dalles 1997)—OR and WA, USA	Pool-and-weir	Two fishways, north and east, 1:15 slope at entrance, 1:32 slope inside	4.40	79.00	24.10	Radio telemetry	98	87	85	563	492	577	Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Columbia R. (McNary 1997)—OR and WA, USA	Pool-and-weir	Two ladders, 9.14-m long, 1:20 slope	5.00	67.06	22.68	Radio telemetry	81	98	79	468	457	577	Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Columbia R. (Wells 1997)—WA, USA	Pool-and-weir	1:20 slope	5.00	21.00	21.00	Radio telemetry	42	96	40	240	231	577	Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Columbia R. (Right Bank Rock Island 1997)—WA, USA	Pool-and-weir	Average of varying set of slopes throughout fishway	5.20	12.50	12.50	Radio telemetry	74	60	44	427	255	577	Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Columbia R. (Fishway Rocky Reach 1997)—WA, USA	Pool-and-weir	1 hairpin ccw turn and one 90° cw turn, 1:16 slope all stretches	6.25	27.70	27.70	Radio telemetry	72	56	40	418	233	577	Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Columbia R. (Priest Rapids 1997)—WA, USA	Pool-and-weir	1:16 slope	6.25	25.60	25.60	Radio telemetry	79	95	75	457	433	577	Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Columbia R. (Left Bank Rock Island 1997)—WA, USA	Pool-and-weir	Average of varying set of slopes throughout fishway	6.70	12.50	12.50	Radio telemetry	74	31	23	427	134	577	Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Columbia R. (Bonneville	Pool-and-weir	Two fishways at each side,	8.13	18.30	18.30	Radio telemetry	100	98	98	577	563	577		

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Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
1997)—OR, USA		1:16 slope at PH1 and 1:10 slope at PH2											Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Columbia R. (Wanapum 1997)—WA, USA	Pool-and-weir	1:10 slope	10.00	25.10	25.10	Radio telemetry	75	99	74	433	427	577	Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Columbia R. (Middle Rock Island 1997)—WA, USA	Pool-and-weir	Average of varying set of slopes throughout fishway	10.00	12.50	12.50	Radio telemetry	74	7	5	427	29	577	Sockeye salmon (*Oncorhynchus nerka*)	Naughton *et al.* (2005)
Neuse R.—(Quaker Neck Dam 1996) NC, USA	Pool-and-weir	25.3-m long, submerged orifice, poor attraction flows, decommissioned in 1998	8.00	2.03	2.03	Radio telemetry	47	0	0	7	0	15	Striped bass (*Morone saxatilis*)	Beasley and Hightower (2000)
Neuse R.—(Quaker Neck Dam 1997) NC, USA	Pool-and-weir	25.3-m long, submerged orifice, poor attraction flows, decommissioned in 1998	8.00	2.03	2.03	Radio telemetry	53	30	16	10	3	19	Striped bass (*Morone saxatilis*)	Beasley and Hightower (2000)
Connecticut R. (Gatehouse D. 2002)—MA, USA	Vertical-slot	Double Hell's Gate vertical-slot with eight pools, 70-m long	3.40	2.40	2.40	PIT tag	100	76	76	25	19	25	American shad (*Alosa sapidissima*)	Sullivan (2004)
Connecticut R. (Gatehouse D. 2001)—MA, USA	Vertical-slot	Double Hell's Gate vertical-slot with eight pools, 70-m long	3.40	2.40	2.40	PIT tag	100	84	84	49	41	49	American shad (*Alosa sapidissima*)	Sullivan (2004)
Connecticut R. (Gatehouse D. 2000)—MA, USA	Vertical-slot	Double Hell's Gate vertical-slot with eight pools, 70-m long	3.40	2.40	2.40	PIT tag	100	81	81	73	59	73	American shad (*Alosa sapidissima*)	Sullivan (2004)
Connecticut R. (Gatehouse D. 1999)—MA, USA	Vertical-slot	Double Hell's Gate vertical-slot with eight pools, 70-m long	3.40	2.40	2.40	PIT tag	100	87	87	91	79	91	American shad (*Alosa sapidissima*)	Sullivan (2004)

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Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
Big Carp R. (2003)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	0	0	0	0	0	1	Brown bullhead (*Ameiurus nebulosus*)	O'Connor *et al.* (2003)
Cobourg Brook (2003)—ON, Canada	Vertical-slot	Vertical-slot with lamprey barrier 4.5-m long	21.00	1.75	0.93	PIT tag	100	100	100	2	2	2	Brown bullhead (*Ameiurus nebulosus*)	O'Connor *et al.* (2003)
Big Carp R. (2003)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	57	100	57	4	4	7	Brown trout (*Salmo trutta*)	O'Connor *et al.* (2003)
Cobourg Brook (2003)—ON, Canada	Vertical-slot	Vertical-slot with lamprey barrier 4.5-m long	21.00	1.75	0.93	PIT tag	100	0	0	1	0	1	Burbot (*Lota lota*)	O'Connor *et al.* (2003)
Cobourg Brook (2003)—ON, Canada	Vertical-slot	Vertical-slot with lamprey barrier 4.5-m long	21.00	1.75	0.93	PIT tag	0	0	0	0	0	1	Common shiner (*Notropis cornutus*)	O'Connor *et al.* (2003)
Big Carp R. (2003)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	29	0	0	2	0	2	Creek chub (*Semotilus atromaculatus*)	O'Connor *et al.* (2003)
Seton River (Seton D. 2005)—BC, Canada	Vertical-slot	Vertical-slot with baffled concrete channel 107-m long	6.90	7.60	7.40	Radio telemetry	22	0	0	2	0	9	Pink salmon (*Oncorhynchus gorbuscha*)	Pon *et al.* (2006)
Big Carp R. (2003)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	32	6	2	18	1	57	Rainbow trout (*Oncorhynchus mykiss*)	O'Connor *et al.* (2003)
Cobourg Brook (2003)—ON, Canada	Vertical-slot	Vertical-slot with lamprey barrier 4.5-m long	21.00	1.75	0.93	PIT tag	12	100	12	2	2	17	Rainbow trout (*Oncorhynchus mykiss*)	Pratt *et al.* (2006)
Cobourg Brook (2005)—ON, Canada	Vertical-slot	Vertical-slot with lamprey barrier 4.5-m long	21.00	1.75	0.93	PIT tag	58	43	25	14	6	24	Rainbow trout (*Oncorhynchus mykiss*)	Pratt *et al.* (2006)
Big Carp R. (2003)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	0	0	0	0	0	1	Rock bass (*Ambloplites rupestris*)	O'Connor *et al.* (2003)
Big Carp R. (2004)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	33	0	0	2	0	6	Rock bass (*Ambloplites rupestris*)	Pratt *et al.* (2006)
Big Carp R. (2005)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	29	50	15	2	1	7	Rock bass (*Ambloplites rupestris*)	Pratt *et al.* (2006)

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Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
Big Carp R. (2003)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	26	43	11	7	3	27	Rock bass (*Ambloplites rupestris*)	Pratt *et al.* (2006)
Cobourg Brook (2003)—ON, Canada	Vertical-slot	Vertical-slot with lamprey barrier 4.5-m long	21.00	1.75	0.93	PIT tag	51	11	6	27	3	53	Rock bass (*Ambloplites rupestris*)	O'Connor *et al.* (2003)
Seton River (Seton D. 2005)—BC, Canada	Vertical-slot	Vertical-slot with baffled concrete channel 107-m long	6.90	7.60	7.40	Radio telemetry	77	100	77	23	23	30	Sockeye salmon (*Oncorhynchus nerka*)	Pon, *et al.* (2006)
Seton River (Seton D. 2007)—BC, Canada	Vertical-slot	Vertical-slot with baffled concrete channel 107-m long	6.90	7.60	7.40	Radio telemetry	86	93	80	44	41	51	Sockeye salmon (*Oncorhynchus nerka*)	Roscoe and Hinch (2008)
Seton River (Seton D. 2008)—BC, Canada	Vertical-slot	Vertical-slot with baffled concrete channel 107-m long	6.90	7.60	7.40	Radio telemetry	86	80	69	51	41	59	Sockeye salmon (*Oncorhynchus nerka*)	Roscoe *et al.* (2009)
Big Carp R. (2003)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	80	7	6	297	20	373	White sucker (*Catostomus commersoni*)	O'Connor *et al.* (2003)
Big Carp R. (2003)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	98	37	36	359	132	366	White sucker (*Catostomus commersoni*)	Pratt *et al.* (2006)
Big Carp R. (2004)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	97	91	88	461	418	475	White sucker (*Catostomus commersoni*)	Pratt *et al.* (2006)
Big Carp R. (2005)—ON, Canada	Vertical-slot	Vertical-slot 6-m long	6.70	1.20	0.40	PIT tag	97	66	64	788	520	812	White sucker (*Catostomus commersoni*)	Pratt *et al.* (2006)
Cobourg Brook (2003)—ON, Canada	Vertical-slot	Vertical-slot with lamprey barrier 4.5-m long	21.00	1.75	0.93	PIT tag	86	35	30	350	121	407	White sucker (*Catostomus commersoni*)	O'Connor *et al.* (2003)
Cobourg Brook (2005)—ON, Canada	Vertical-slot	Vertical-slot with lamprey barrier 4.5-m long	21.00	1.75	0.93	PIT tag	85	11	9	225	24	265	White sucker (*Catostomus commersoni*)	Pratt *et al.* (2006)
Cobourg Brook (2003)—ON, Canada	Vertical-slot	Vertical-slot with lamprey barrier 4.5-m long	21.00	1.75	0.93	PIT tag	82	7	6	243	18	296	White sucker (*Catostomus commersoni*)	Pratt *et al.* (2006)

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Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
East River (Steeppass 2 2007)—Guilford, CT	Denil	3.05-m long, 0.57-m wide, 0.68-m deep	9.60	0.29	0.29	PIT tag	–	95	–	91	86	91	Alewife (*Alosa pseudoharengus*)	Franklin (2009)
East River (Steeppass 1 2007)—Guilford, CT	Denil	3.05-m long, 0.57-m wide, 0.68-m deep	29.60	0.90	0.90	PIT tag	100	97	97	146	141	146	Alewife (*Alosa pseudoharengus*)	Franklin (2009)
Grand R. (Mannheim Weir West)—ON, Canada	Denil	27-m long, double-back, three parallel flumes with baffles 25 cm apart	10.00	2.20	2.15	Radio telemetry	82	36	30	43	16	53	Smallmouth bass (*Micropterus dolomieu*)	Bunt *et al.* (1999)
Grand R. (Mannheim Weir East)—ON, Canada	Denil	Single 11-m concrete flume	20.00	2.20	2.15	Radio telemetry	55	33	18	29	10	53	Smallmouth bass (*Micropterus dolomieu*)	Bunt *et al.* (1999)
Grand R. (Dunnville)—ON, Canada	Denil	Three baffles with pools in 47×1.35 m concrete channel	10.50	4.40	4.40	Radio telemetry	21	0	0	5	0	24	Walleye (*Sander vitreus vitreus*)	Bunt *et al.* (2000)
Grand R. (Mannheim Weir West)—ON, Canada	Denil	27-m long, doubles-back, three parallel flumes with baffles 25 cm apart	10.00	2.20	2.15	Radio telemetry	50	55	28	16	9	32	White sucker (*Catostomus commersoni*)	Bunt *et al.* (1999)
Grand R. (Mannheim Weir East)—ON, Canada	Denil	Single 11-m concrete flume	20.00	2.20	2.15	Radio telemetry	59	38	22	19	7	32	White sucker (*Catostomus commersoni*)	Bunt *et al.* (1999)
Town Brook (Rock Ramp 2006)—Plymouth, MA	Nature-like	Boulder ramp 32-m long, 8-m wide	4.20	1.33	1.33	PIT tag	100	94	94	103	97	103	Alewife (*Alosa pseudoharengus*)	Franklin (2009)
East River (Channel 2 2007)—Guilford, CT	Nature-like	7- to 9-m wide with boulders in 13 step pools	7.10	1.19	1.19	PIT tag	–	65	–	141	91	141	Alewife (*Alosa pseudoharengus*)	Franklin (2009)

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Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
East River (Channel 1 2007)—Guilford, CT	Nature-like	7- to 9-m wide with boulders in 13 step pools	7.10	0.97	0.97	PIT tag	92	69	63	212	146	231	Alewife (*Alosa pseudoharengus*)	Franklin (2009)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	50	50	25	2	1	4	Baltic vimba (*Vimba vimba*)	Calles and Greenberg (2007)
Tirsbaek Brook (1999/2000)—Denmark	Nature-like	130-m long	1.70	2.20	2.20	PIT tag	91	60	55	30	18	33	Brown trout (*Salmo trutta*)	Aarestrup *et al.* (2003)
R. Eman (Upper Finsjo 2001)—Sweden	Nature-like	150-m long	1.80	4.20	2.70	PIT tag	50	100	50	12	12	24	Brown trout (*Salmo trutta*)	Calles and Greenberg (2005)
R. Eman (Upper Finsjo 2002)—Sweden	Nature-like	150-m long	1.80	4.20	2.70	PIT tag	53	100	53	17	17	32	Brown trout (*Salmo trutta*)	Calles and Greenberg (2005)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	20	92	18	26	24	132	Brown trout (*Salmo trutta*)	Calles and Greenberg (2005)
R. Eman (Lower Finsjo 2002)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	14	91	13	35	32	253	Brown trout (*Salmo trutta*)	Calles and Greenberg (2005)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	57	50	29	4	2	7	Brown trout (*Salmo trutta*)	Calles and Greenberg (2007)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	83	60	50	5	3	6	Burbot (*Lota lota*)	Calles and Greenberg (2007)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	38	86	33	13	11	34	Chub (*Squalius cephalus*)	Calles and Greenberg (2007)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	10	100	10	1	1	10	Common bream (*Abramis brama*)	Calles and Greenberg (2007)

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Location	Structure type	Design	Slope (%)	Structure height (m)	Elevation change (m)	Monitoring method	Attn (%)	Pass (%)	Total eff.	*N* entering	*N* exiting	*n*	Species	Source
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	13	0	0	1	0	8	Northern pike (*Esox lucius*)	Calles and Greenberg (2007)
Welland R. (Port Davidson Weir)—ON, Canada	Nature-like	12-m long, 0.9-m-wide channel	3.70	0.65	0.65	Radio telemetry	80	100	80	8	8	10	Northern pike (*Esox lucius*)	Bunt (2003)
Oswego Ck. (Canborough Weir)—ON, Canada	Nature-like	0.8-m wide in three sections 42-m long (8.5 m, 25.9 m, 7.5 m)	4.00	1.00	1.00	Radio telemetry	100	100	100	5	5	5	Northern pike (*Esox lucius*)	Bunt (2003)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	32	100	32	8	8	25	Perch (*Perca fluviatilis*)	Calles and Greenberg (2007)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	23	50	12	10	5	44	Roach (*Rutilus rutilus*)	Calles and Greenberg (2007)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	3	0	0	1	0	31	Rudd (*Scaridinus erythropthalmus*)	Calles and Greenberg (2007)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	50	100	25	7	7	14	Tench (*Tinca tinca*)	Calles and Greenberg (2007)
R. Eman (Lower Finsjo 2001)—Sweden	Nature-like	370-m long	2.50	14.50	9.25	PIT tag	0	0	0	0	0	4	Zander (*Sander lucioperca*)	Calles and Greenberg (2007)

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