

RESEARCH ARTICLE OPEN ACCESS

Riverine Migration Success of Salmonid Smolts Following Their Entrainment in a Hydropower Off-Channel Diversion in an Upland River

Bertram I. C. Warren | J. Robert Britton 

Department of Life and Environmental Sciences, Bournemouth University, Poole, UK

Correspondence: J. Robert Britton (rbritton@bournemouth.ac.uk)

Received: 27 August 2025 | **Revised:** 6 December 2025 | **Accepted:** 31 March 2026

Keywords: acoustic telemetry | Atlantic salmon | brown trout | migration success

ABSTRACT

Salmonid fishes typically express anadromy. During their juvenile riverine emigration, their downstream movements can be inhibited by hydropower schemes that entrain fish in their intakes. Here, the riverine migration success of smolts of brown trout *Salmo trutta* (“trout smolt”) and Atlantic salmon *Salmo salar* smolts (“salmon smolt”) was measured in a moorland-fed spate river in southwest England. This river has some weirs and run-of-river hydropower schemes throughout its length that potentially inhibit smolt emigration through entrainment (hydropower) and passage delay (low-head weirs). The capture of entrained fish from an off-channel diversion for a run-of-river hydropower scheme in the upper river late in the smolt migration window enabled their implantation with an acoustic transmitter. These smolts were then released into the main river channel and their downstream migration tracked. Of 58 tagged smolts released, 39 were detected at least once in the river, with 27 detected as migrating successfully to the lower river/estuary. The trout smolts that reached the estuary were of similar size to those that were unsuccessful, whereas salmon reaching the estuary were significantly larger than unsuccessful individuals. While downstream smolt movements were not inhibited by the weirs or hydropower schemes, the migration period was characterised by high river levels, with some smolts reaching the estuary in less than 3 days. These results reveal that migration success rates of these smolts were relatively high following their release back into the main river channel, suggesting that smolt capture and release following entrainment can represent a successful mitigation strategy.

1 | Introduction

Migration requires genetic and/or learnt instructions about the timing, duration and distance of movements, evolved behavioural and physiological adaptations, and the ability to orientate and navigate (Thorup et al. 2017; Mouritsen 2018). Migration has evolved to enable individuals to maximize their fitness in seasonal environments but exists in a trade-off with its costs (e.g., time, energy and mortality) (Chapman et al. 2013; Lok et al. 2015). Multiple selection pressures can act on migration, including the effect of variability in thermal and precipitation regimes on whether a migrant is successful (Gill et al. 2014;

La Sorte et al. 2016). For diadromous fishes, artificial selection pressures include the presence of anthropogenic riverine barriers and artificial river channels (“off-channel diversions” hereafter) that individuals must navigate over or through in order to complete their migration (Meixler et al. 2009; Marschall et al. 2011). There are now multiple barriers present on many rivers around the world (Grill et al. 2019), where on rivers in Great Britain, there is a barrier, on average, every 1.5 km (Jones et al. 2019).

In juvenile anadromous salmonid fishes, the timing of their transition from freshwater to their marine life stage (“smolting”) is

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *River Research and Applications* published by John Wiley & Sons Ltd.

generally cued by photoperiod and temperature, but with actual emigration timing often influenced by elevated stream flows that initiate the actual downstream movement (Otero et al. 2014). These high flow events then generally result in higher migration success in both free-flowing and fragmented rivers, where in the latter, the higher flows reduce migration delays at barriers (Gauld et al. 2013). As the fish move downstream, they use cues from their physical environment to help select routes favourable for these movements (Haraldstad et al. 2017).

On rivers where run-of-river hydropower schemes have been installed, water can be diverted from the main river channel into an off-channel diversion. The diversion can then direct the water for several hundred metres before it passes through the turbine and is then returned to the river further downstream. In the area of river immediately upstream of the diversion, the altered flow regime can attract fish into the diversion due to most of the flow being directed into the channel (Gibeau et al. 2017). Once in the off-channel diversion, the downstream migration of the fish can be inhibited if they are unable to move back into the main river channel, such as due to their downstream passage being inhibited by the turbine and/or due to insufficient structures being present to facilitate their passage around the turbine (Boubée and Williams 2006; Gibeau et al. 2017). These off-channel diversions for hydropower can thus act as ecological traps for smolts as they impede and potentially prevent their riverine migration, so impacting individual fitness (Ohms et al. 2022). In some river systems impacted by large hydropower dams that lack fish passage facilities, salmonid smolts are captured upstream and transported and released downstream of the dam (“trap-and-haul”) (Sigourney et al. 2015; Lusardi and Moyle 2017). The performance and effectiveness of these translocations can vary within rivers according to the prevailing numbers of fish moved and the abiotic conditions (Colvin et al. 2018), and with variation also apparent between rivers and across different timescales (Kock et al. 2021).

In the last decade, there has been a substantial increase in knowledge of salmonid smolt migration success from many rivers due to advances in acoustic telemetry that now enable transmitter implantation into relatively small fish (e.g., Rodger, Guthrie, et al. 2024; Rodger, Lilly, et al. 2024). A large focus of this work has been on Atlantic salmon *Salmo salar* smolts moving out of rivers and into the marine environments of the northern British Isles. For example, measured migration success rates have varied from 4% to 97% across 22 rivers, with between year variations of 3% to 61%, with this variation driven by environmental drivers acting locally (Rodger, Guthrie, et al. 2024). Passage rates of salmon smolts across small-scale hydropower dams can be high, but individuals can be delayed by having to make several attempts at passage before being successful (Rodger et al. 2025). For anadromous brown trout *Salmo trutta* smolts, impoundments and artificial lakes can slow their downstream progression, where individuals express erratic movement patterns and with overall passage rates being impacted (Schwinn et al. 2018). The removal of artificial structures can promote smolt passage, which may increase overall migration success and prepone the peak of the migration period (Birnie-Gauvin et al. 2018). Early migration can result in increased rates of survival (Jensen et al. 2022), and thus the timing of riverine migration may have important influences on the health of migratory fish stocks.

Climate change is predicted to affect the distribution of many fish species due to the combined effects of warming and changes in precipitation (e.g., Graham and Harrod 2009; Ruiz-Navarro et al. 2016a). In Great Britain, predictions from climate envelope models suggest that during this century, populations of both brown trout and Atlantic salmon will increasingly be constrained to upland areas of Wales and, under low emission scenarios, areas of northern England and Scotland, with many populations in southern England becoming extirpated (Ruiz-Navarro et al. 2016b). The exceptions are salmonid populations in the moorland fed rivers of southwest England, where population persistence is predicted throughout the century as these upland areas should maintain their relatively low air temperatures and high rainfall (Ruiz-Navarro et al. 2016b). The Atlantic salmon populations in these rivers are generally in decline (Environment Agency 2024a, 2024b). Consequently, these salmon populations have high conservation importance due to their combination of population decline and predicted persistence in a warming climate. There is, however, a paucity of information on smolt migrations from these rivers, including how the effects of barriers and run-of-river hydropower systems affect smolt migration success.

The aim of this study was to thus assess salmonid smolt migration success from the River Teign, a river whose source is on Dartmoor, southwest England (Figure 1). Due to the high energy of the upper river, there is a series of run-of-river hydropower schemes present that use off-channel diversions to redirect water from the main river and into the turbine before the water is returned further downstream. Fish passage around the turbine is usually facilitated by an alternative channel (“by-wash”). The main river section between the channel intake and outflow is thus depleted in its flow. In this study, smolts of both Atlantic salmon (Linnaeus, 1758) (“salmon”) and brown trout (Linnaeus, 1758) (“trout”) were observed as being present within an off-channel hydropower diversion in the upper River Teign catchment late in the 2024 smolt run period (Figure 1). These fish were considered as being entrained in this channel due to the relatively high numbers observed as present over the smolt run period. Consequently, these fish were captured and then released into the adjacent main river downstream of the intake of the off-channel diversion (i.e., small-scale trap-and-transport). Prior to their release, these individuals were implanted with an acoustic transmitter that enabled tracking of their downstream migration. Objectives were to (i) measure the overall riverine migration success of the released smolts of both species and their migration time (time between tagging and detection in the lower river, and from first detection in the river and to their first detection in the lower river); and (ii) their downstream passage rates across weirs and through hydropower diversion channels located downstream of the release site. Factors affecting the migration success of these smolts, and consideration of the efficacy of capturing and releasing entrained smolts, are then discussed.

2 | Materials and Methods

2.1 | Study Area

The River Teign is an upland spate river in Devon, southern England. The river drains part of the moorland area of Dartmoor and flows for approximately 50 km from its source (50°38'19" N; 3°57'31" W) to its tidal limit below Newton

Abbott (50°32'11" N; 3°35'14" W) (Figure 1). Its fish assemblage is largely dominated by anadromous Atlantic salmon and brown trout, with the latter comprising both river resident and anadromous forms. The catchment is characterised by a series of barriers (weirs) and off-channel hydropower diversions (Figure 1; Table 1). There is concern that the weirs throughout the catchment delay the downstream movement of the salmonid smolts, and the smolts that enter the hydropower diversions become entrained.

This study was completed during spring 2024, a period in which the River Teign catchment experienced an exceptionally wet period, with a rainfall monitoring station located in the upper catchment (50°40'48" N; 3°44'19" W) recording 440.7 mm of rainfall between 01/03/24 and 31/05/24 versus 193.0, 127.3, 267.3, 177.3 and 335.6 mm in the same periods of 2019 to 2023 respectively (Department for Environment, Food and Rural Affairs 2025). This rainfall in spring 2024 resulted in sustained high river levels and flows.

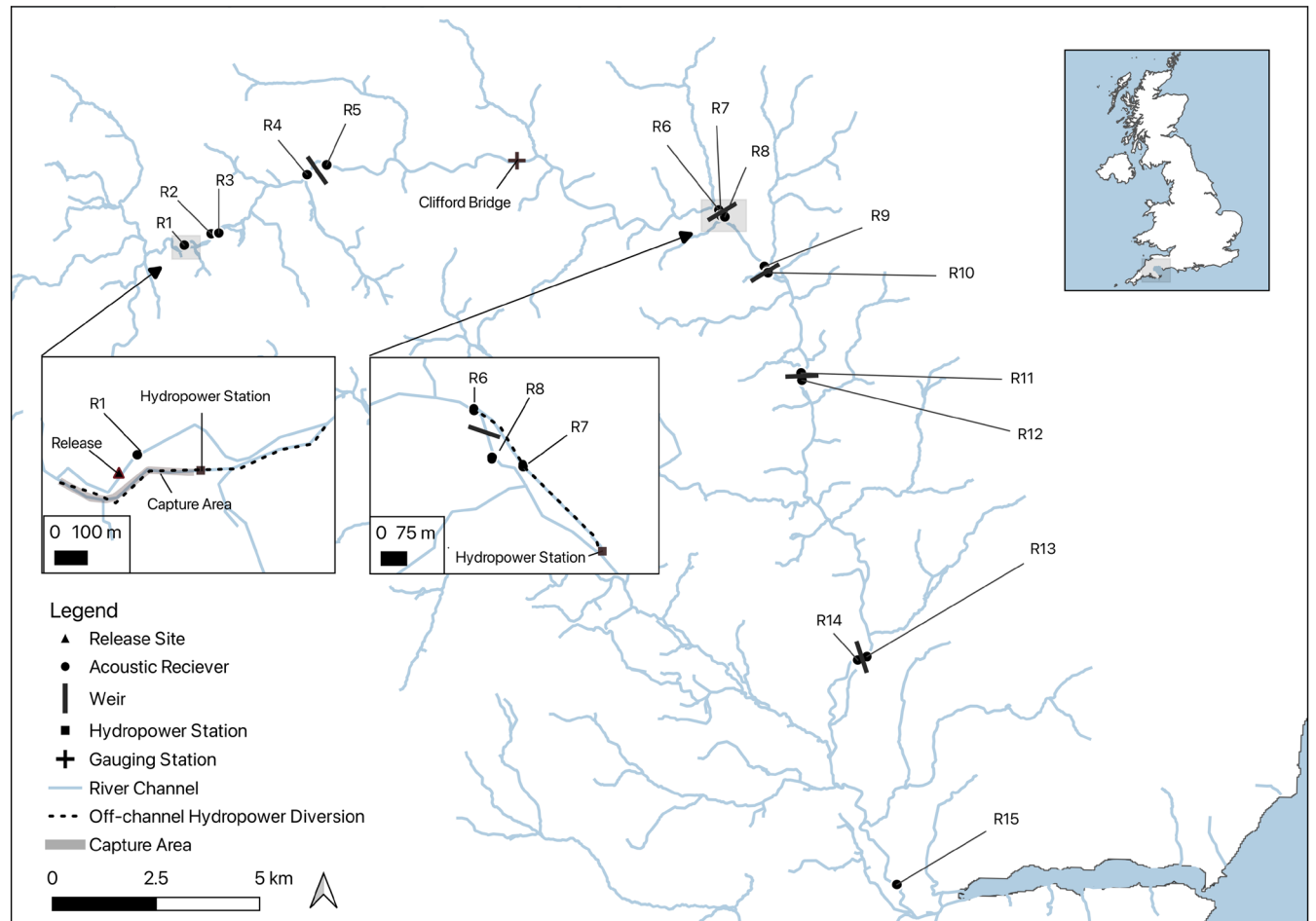


FIGURE 1 | Map of the River Teign study area, showing acoustic receiver locations (black points), release site (black triangle), weirs (black lines) and HEP (black squares)/off-channel diversions (dashed lines), (inset) the location of the diversions and (inset) the study area in the wider context of the islands of Great Britain and Ireland. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rra.70144)]

TABLE 1 | Number of detections and smolts (combined by species) per location and receiver number (cf. Figure 1) (u/s, upstream; d/s, downstream; ocd, off-channel hydropower diversion).

Location	Upstream			1st barrier		Sowton			Bridford weir		Ryecroft		Chudleigh		Estuary
	1	2	3	4 (u/s)	5 (d/s)	6 (u/s)	7 (ocd)	8 (d/s)	9 (u/s)	10 (d/s)	11 (u/s)	12 (d/s)	13	14	
Receiver (R)	1	2	3	4 (u/s)	5 (d/s)	6 (u/s)	7 (ocd)	8 (d/s)	9 (u/s)	10 (d/s)	11 (u/s)	12 (d/s)	13	14	15
N detections	0	0	0	5690	0	0	272	37	0	0	0	18	526	0	76
N smolts detected	0	0	0	27	0	0	25	2	0	0	0	3	26	0	22

2.2 | Fish Capture and Tagging, and Acoustic Receiver Network

An off-channel diversion located in the upper river catchment was used for smolt capture, where the presence of these smolts in the diversion suggested that they were being prevented from rejoining the main river channel and continuing their downstream migration (Figure 1). The channel was a maximum of 4 m width and 1.3 m depth, with back mounted, battery powered electric fishing equipment (SmithRoot LR24) used to capture fish on 26/04/2024 and 29/04/2024. All captured fish were then held in river water filled containers with aeration. Individual fish were then anaesthetised (buffered ethyl 3-aminobenzoate methanesulfonate; MS-222; 0.4 g/L), measured (fork length (FL), nearest mm), and internally implanted (peritoneal cavity) with a Vemco V7T acoustic transmitter (180 kHz; 7 × 16 mm; 1.2 g in air, 137 dB RE 1 µPa) (www.innovasea.com). The incision into the peritoneal cavity was then closed using a single absorbable monofilament suture (4–0). Acoustic transmitter programming was a randomised 1-min pulse interval (minimum-maximum interval 40–80 s), providing a battery life of approximately 152 days. The transmitter was equipped with a temperature sensor, which generated sensor values (°C) for each detection (accuracy ±0.5°C, precision 0.15°C). A total of 58 salmonid smolts (15 salmon, 35 trout; Table 2) were implanted with a transmitter and then released into the adjacent main river channel (depleted section) (Figure 1).

To migrate downstream from the release site to the river estuary, the smolts must pass at least five weirs of approximately 2 m head-height under normal river conditions, and they encounter a further two run-of-river hydropower schemes involving an off-channel diversion (Figure 1). The total river distance between the release site and the upper river estuary was 38 km. Across this river distance, a total of 15 acoustic receivers were deployed at seven strategic locations (Figure 1; Table 1). A smolt was considered as successfully migrating downstream when it was detected on receiver R15 in the upper estuary (Figure 1; Table 1). However, due to receiver inefficiencies, those smolts detected on R13, 7 km upstream of R15, were also considered as successful migrants (*cf.* Results). The 15 receivers also enabled the tracking of the downstream passage of smolts over the major weirs and their movement through another off-channel hydropower diversion (Figure 1; Table 1). Contrary to best practice (Kessel et al. 2014)—but necessary to the sustained high river conditions that provided very short windows of receiver deployment opportunities—the acoustic receivers were deployed without range testing being completed. Range testing was instead completed in July 2024 during lower river conditions. This testing indicated that in the upper river (with river widths to 12 m and depths to 1.5 m in normal flows), typical detection ranges were up to 40 m up- and downstream. However, longer ranges (> 80 m) were recorded in the lower river. This limited detection range of receivers in the upper river, coupled with the pulse interval programmed on the V7T transmitters (40–80 s) and the general noise of this high energy upper river, resulted in some issues with receiver detection efficiencies. Accordingly, receiver efficiencies were calculated by determining the number of fish detected on a receiver as a proportion of the total number of

fish detected at least once on receivers downstream in order to understand how these inefficiencies affected the subsequent smolt detections (Flávio et al. 2021).

2.3 | Data Analyses

The detection data downloaded from the receivers were processed using the function *migration* within the *actel* R package (Flávio et al. 2021). Initial analyses were to determine the number of smolts per species that were detected at least once, the number detected as moving downstream and then the number that were detected in the lower river on R13/R15 (i.e., their migration success rate). For those smolts detected as moving downstream, calculations were for the time between (i) their release and first detection (generally, but not always, R4) (Tables 1, 2) and (ii) release/first detection to their first detection on the receivers downstream (R13/R15). For those smolts detected in the lower river, the time between their initial detection following their release and their first detection in the lower river (R13/R15) was determined. These data enabled the speed of downstream movement of each fish to be determined in *actel*, where speed limits and skipping arrays were not set in the software due to the efficiencies of some receivers being low in some of the river sections (*cf.* Results). However, the data for each fish were inspected manually, with no unrealistic detections or abnormal movements detected and so no data were removed. To explore patterns in migration across the diel cycle, the times of first detection at each receiver were gathered and plotted using *actel*; data were only included from receivers of relatively high detection efficiency (*cf.* Results).

To test the effect of a range of fixed factors a range of migration times, generalised linear models (GLM) were fitted (Gamma distribution, log link function). The response variables were the (i) time between tagged smolt release to first upstream detection; (ii) time between tagged smolt release to first detection in the lower river; and (iii) first detection at the first barrier to the first detection in the lower river. The initial fixed factors selected for testing were river level (m; sourced from Clifford Bridge) (<https://check-for-flooding.service.gov.uk/station/3214>; Figure 1), temperature (using the transmitter sensor values), time since sunset in Dartmoor National Park (from <https://www.timeanddate.com/sun/@10244122>), Julian day of year, species (trout/salmon) and fish length. Prior to model construction, the correlation coefficients (Pearson's) of these parameters were checked; where significant correlations were $r > 0.70$, one of the variables was removed. This resulted in the removal of photoperiod and temperature from the dataset as they were significantly correlated with Julian day of year. Model selection was performed using stepwise Akaike's Information Criterion (AIC then explore). To then assess the relationship between smolt speed (km day^{-1}) and the distance travelled downstream, a GLM (Gamma distribution, log link function) tested the response variable of speed between receivers for each step versus the fixed factors of cumulative distance downstream (km), species and fish length. All analyses were conducted in R (R Core Team 2024). Mean values ($\pm 95\%$ confidence intervals) were reported for normally distributed data and used parametric tests when all assumptions were

TABLE 2 | Transmitter codes, tagging date, species (BT, Brown trout smolt; S, Atlantic salmon smolt), fish fork length (FL) and number of detections in total and by receiver location.

Transmitter	Tagging date	Spp.	FL (mm)	<i>n</i> total detections	<i>n</i> detections per receiver/ location (Figure 1)				
					R4	R7	R8	R13	R15
A180-1704-1315	26/04/2024	BT	158	49		2		5	42
A180-1704-1374	29/04/2024	BT	163	1013	1003	2		3	5
A180-1704-1324	26/04/2024	BT	157	12	3	2		5	2
A180-1704-1338	29/04/2024	BT	244	12	5	2		3	2
A180-1704-1353	29/04/2024	BT	158	13	7	2		2	2
A180-1704-1352	29/04/2024	BT	157	8	4			2	2
A180-1704-1375	29/04/2024	BT	144	343	3	2		337	1
A180-1704-1341	29/04/2024	BT	172	61	14		36	10	1
A180-1704-1346	29/04/2024	BT	182	9		2		6	1
A180-1704-1311	26/04/2024	BT	162	14	6	2		5	1
A180-1704-1381	29/04/2024	BT	155	12	6	1		4	1
A180-1704-1329	29/04/2024	BT	162	6		1		4	1
A180-1704-1312	26/04/2024	BT	144	10	5		1	3	1
A180-1704-1345	29/04/2024	BT	170	8	3	2		2	1
A180-1704-1349	29/04/2024	BT	165	6	1	3		1	1
A180-1704-1307	26/04/2024	BT	173	4	2			1	1
A180-1704-1306	26/04/2024	BT	152	3	2				1
A180-1704-1310	26/04/2024	BT	188	108	2	9		97	
A180-1704-1316	26/04/2024	BT	188	69		62		7	
A180-1704-1343	29/04/2024	BT	152	8	7			1	
A180-1704-1308	26/04/2024	BT	201	5		5			
A180-1704-1326	26/04/2024	BT	152	2		2			
A180-1704-1332	29/04/2024	BT	175	3123	3123				
A180-1704-1323	26/04/2024	BT	167	1460	1460				
A180-1704-1351	29/04/2024	BT	176	5	5				
A180-1704-1350	29/04/2024	BT	160	1	1				
A180-1704-1300	26/04/2024	BT	319	0					
A180-1704-1304	26/04/2024	BT	237	0					
A180-1704-1305	26/04/2024	BT	158	0					
A180-1704-1313	26/04/2024	BT	147	0					
A180-1704-1314	26/04/2024	BT	148	0					
A180-1704-1317	26/04/2024	BT	141	0					
A180-1704-1318	26/04/2024	BT	162	0					
A180-1704-1319	26/04/2024	BT	162	0					
A180-1704-1320	29/04/2024	BT	160	0					

(Continues)

TABLE 2 | (Continued)

Transmitter	Tagging date	Spp.	FL (mm)	<i>n</i> total detections	<i>n</i> detections per receiver/ location (Figure 1)				
					R4	R7	R8	R13	R15
A180-1704-1327	29/04/2024	BT	153	0					
A180-1704-1331	29/04/2024	BT	148	0					
A180-1704-1339	29/04/2024	BT	152	0					
A180-1704-1340	29/04/2024	BT	173	0					
A180-1704-1322	29/04/2024	BT	159	0					
A180-1704-1342	29/04/2024	BT	136	0					
A180-1704-1344	26/04/2024	BT	175	0					
A180-1704-1347	29/04/2024	BT	232	0					
A180-1704-1309	26/04/2024	S	168	7				3	4
A180-1704-1337	29/04/2024	S	164	9				6	3
A180-1704-1301	26/04/2024	S	167	11	3	2		5	1
A180-1704-1303	26/04/2024	S	152	10	2	2		5	1
A180-1704-1376	29/04/2024	S	184	4	1	1		1	1
A180-1704-1336	29/04/2024	S	180	22	15	2		5	
A180-1704-1377	29/04/2024	S	141	9	3	3		3	
A180-1704-1335	29/04/2024	S	138	81		81			
A180-1704-1325	26/04/2024	S	128	51		51			
A180-1704-1333	29/04/2024	S	126	26		26			
A180-1704-1321	26/04/2024	S	145	3		3			
A180-1704-1334	29/04/2024	S	132	3	3				
A180-1704-1348	29/04/2024	S	128	1	1				
A180-1704-1302	26/04/2024	S	142	0					
A180-1704-1330	29/04/2024	S	147	0					

met; with median values (inter-quartile range) reported for non-normal data and where non-parametric tests were used.

3 | Results

3.1 | Receiver Efficiencies

Of the 58 tagged smolts, 39 were detected at least once on one of the receivers (Tables 1 and 2). There were four receiver locations that enabled the tracking of smolts through the river: R4 (upstream of the first barrier), R7/R8 (Sowton run-of-river hydropower), R13 (Chudleigh weir) and R15 (upper Estuary) (Figure 1; Tables 1 and 2). The initial three receivers upstream of the first barrier had no detections (0% efficiency), with R4 being the first receiver with smolt detections, it being located immediately upstream of the first major weir ($n = 27$ smolts; Figure 1). The river distance between the release site and this receiver (R4) was 4 km. Receiver R4 had a detection efficiency of 69%, R7/R8 of 82%, and R13 of 96% (Tables 1 and 2).

3.2 | Smolt Detections on Receivers

Across the receivers in these four locations, the 39 detected smolts were detected on a total of 6622 occasions (Tables 1 and 2). Of the 39 detected fish, 26 were brown trout smolts (mean length: 168 ± 8 mm) and 13 were salmon smolts (mean length: 150 ± 11 mm). Of the 19 tagged fish that were never detected in the river, 16 were brown trout (mean length: 175 ± 22 mm) and 3 were salmon (155 ± 12 mm) (Figure 2). The differences in the lengths of detected versus undetected trout were not significant (ANOVA: $F_{1,40} = 0.39$, $p = 0.54$), although the range of detected fish (144 to 244 mm) was smaller than that of undetected fish (136 to 305 mm) (Figure 2). The undetected fish were not considered further in analyses.

3.3 | Migration Success Rates and Transit Times

Of the 39 fish detected in the river, 27 were detected in the lower river/estuary on R13 and/or R15 (69%). Of the 26 detected

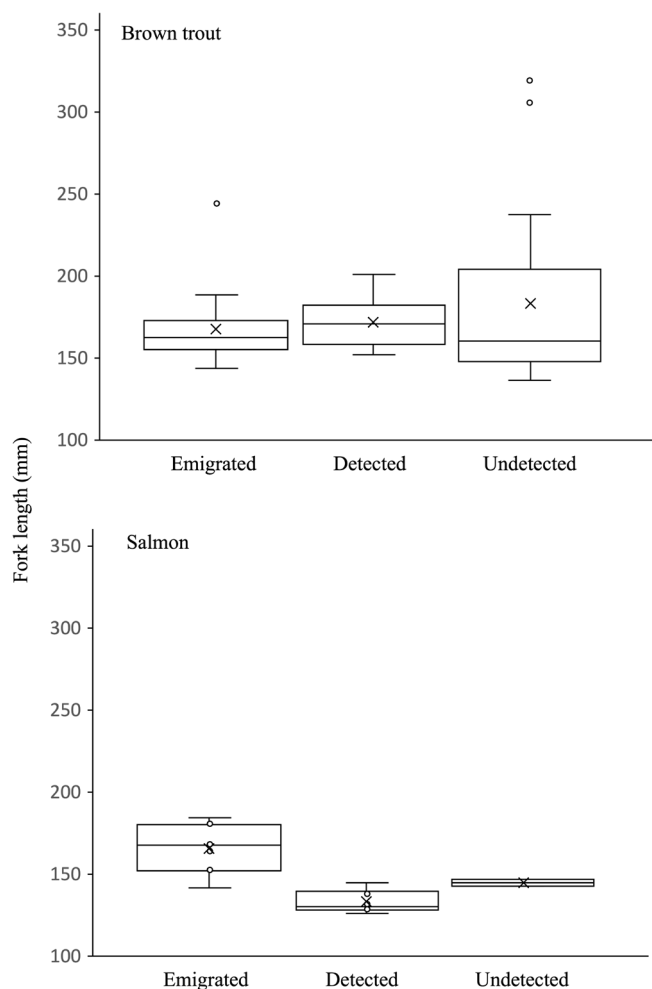


FIGURE 2 | Box plots of the lengths of tagged brown trout and Atlantic salmon smolts that were detected in the lower river (Emigrated), that were detected but not the lower river (Detected) and were never detected (Undetected). Horizontal lines represent 25th, 50th and 75th percentile, vertical lines are 10th and 90th percentile, x =mean and clear circles=outliers. For brown trout, differences in length between fish detected in the lower river, detected upstream but not in the lower river, and those not detected at all were not significant ($F_{2,40}=0.20$; $p=0.82$). For salmon, differences between the groups were significant ($F_{2,12}=12.50$; $p<0.001$), where the significant differences were between the larger successful smolts and the unsuccessful smolts ($p<0.01$); note there were only two undetected salmon smolts.

brown trout, 20 were detected on R13 and/or R15 (77%), and of the 13 detected salmon, 7 were detected on R13 and/or R15 (54%). Differences in the length of brown trout that were and were not detected in the lower river were not significant (median (IQR): 162 (157–172) mm, 171 (162–176) mm respectively; Mann Whitney U test: $z=-0.94$, $p=0.35$), but salmon detected in the lower river were significantly larger than those that were not detected there (median (IQR): 167 (158–174) mm, 138 (128–147) mm respectively; $z=-2.54$, $p=0.01$) (Figure 2).

For all smolts (trout and salmon combined) that were detected at least once in the river, the median time between their release and their first detection was 3.33 days (2.56–6.11 days) ($n=39$), with similar values for those that were successfully detected in the lower river (3.33 days) (0.27–3.71 days) ($n=27$)

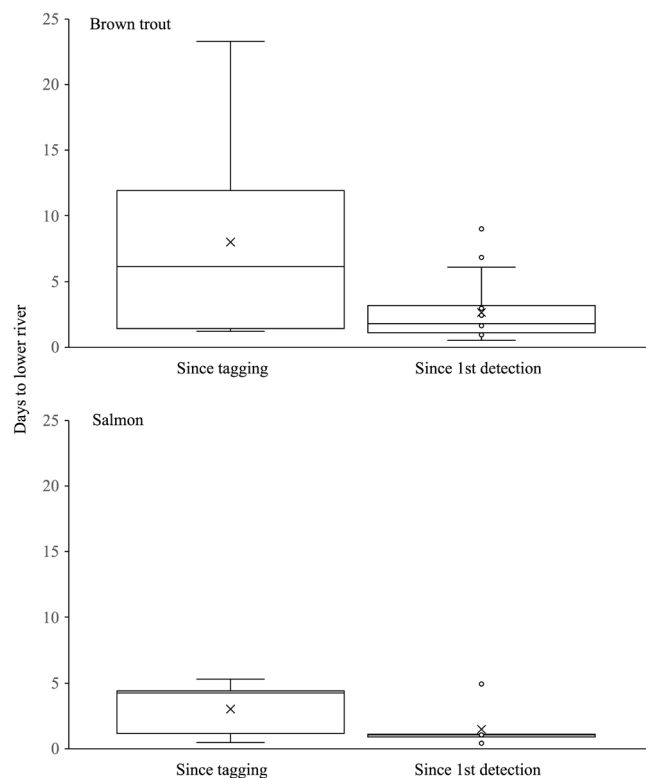


FIGURE 3 | Box plots of days to emigrate since tagging and since the first detection of brown trout and Atlantic salmon smolts.

(Figure 3). The median time between release and smolt detection in the lower river was 4.78 days (4.26–7.53 days). The median time between their first upstream detection and first detection in the lower river was 1.21 days (1.02–10.37 days) (Figure 3). The GLMs testing the time between first detections post-tagging/at first barrier to the first detection in the lower river both had significant effects of river level and time since dusk, with these times decreasing with higher river levels and time since dusk (Table 3). Species did not have a significant effect in any model (Table 3). The mean speed of downstream movements from 1st detection to the lower river was $23.8 \pm 3 \text{ km day}^{-1}$. The rate at which smolts moved downstream was significantly and positively related to the distance downstream of their last detection (GLM: $z=2.5$, $p=0.02$), but there was no difference between the species ($z=-0.19$, $p=0.84$) and body length did not have a significant effect ($z=0.04$, $p=0.97$).

3.4 | Detection Times of Movements/Arrival

The downstream movements of the smolts primarily occurred in the dark, although there were also some detections in daylight periods (Figure 4). Mean times of arrival at the R4, R13 and R15 were at 02:28:52, 03:49:27 and 02:57:23 respectively, with the mean time of last detection at R15 also being at night 02:48:20 (Figures 1 and 4). The longest duration that fish remained at a given location was above the first barrier (R4: $4.19 \pm 12.80 \text{ h}$), with minimal time spent in the off-channel diversion at Sowton (R7: $0.09 \pm 0.30 \text{ h}$) and upstream of the weir at Chudleigh (R13: $0.38 \pm 1.36 \text{ h}$).

TABLE 3 | Coefficient estimates, standard errors, z scores and their significance (*p*) from results of each best fitting generalised linear model (gamma distribution) testing the binary response of migration times from when a smolt was (A) released to their first detection, (B) released to their first detection in the lower river and (C) first detected at the 1st barrier to their first detection in the lower river.

	Estimate	Std. error	z	p
(A)				
Intercept	−9.13	1.63	−5.59	<0.01
Julian day of year	0.12	0.01	9.80	<0.01
Length	−0.01	<0.01	−3.21	<0.01
Species	0.26	0.17	1.57	0.13
(B)				
Intercept	−5.76	1.25	−4.61	<0.01
Julian day of year	0.07	0.01	8.51	<0.01
River level	−0.97	0.32	−3.06	0.01
Dusk	−0.36	0.16	−2.22	0.04
(C)				
Intercept	3.99	0.34	11.73	<0.01
River level	−2.03	0.80	−2.53	0.02
Dusk	−1.09	0.46	−2.40	0.03
Species	−0.75	0.38	−1.99	0.06

Note: Bold text indicates significant factors. Dusk: time since dusk.

3.5 | Effects of Weirs and Hydropower Off-Channel Diversions on Smolt Emigration

The first major barrier the fish encountered downstream of their release sites was a weir of approximate height 1.1 m located just downstream of R4. There were six smolts detected here that were never detected further downstream, although the reason for their failure to migrate downstream was not known. The median time between the initial and final detection of smolts at R4 was 218 s (98–379 s), suggesting no major passage delay for those fish that moved downstream of the weir, although actual passage time was unable to be determined due to the inefficiency of R5 (Table 1). No other weirs were detected as causing any passage delays. The receivers R7 and R8 provided the opportunity to track the tagged smolts through either the main river or the off-channel diversion for a run-of-river hydropower unit (Archimedes screw). Of 27 smolts detected in this location (Figure 1), 2 were detected moving through the main river and 25 through the diversion. The median time between initial and final detection in the diversion was 70 s (52–75 s), suggesting this diversion did not incur any passage delays, with 24 of these smolts successfully being detected on R13/R15.

4 | Discussion

The results indicated that while the overall success of the tagged salmonid smolts in reaching the lower river from the tagging site was 27 of 58 fish, 19 of the tagged fish were not detected at all, most probably due to not running downstream (e.g., some of the larger tagged brown trout), death (e.g., being predated by a piscivorous bird or mammal soon after tagging), or through tag loss. Of the 39 smolts that were detected in the river, 69% were detected on the most downstream receivers in the river (R13/R15). The brown trout smolts detected in the lower river were not significantly different in length than those that were not detected, whereas successful salmon were considerably and significantly larger than those not detected downstream. There was no evidence to suggest barriers (weirs) or the other off-channel hydropower diversions on the river were causing migration delays and so these aspects are not considered further here.

The study period was preceded by a prolonged period of high precipitation in the River Teign catchment, with rainfall totals in the upper catchment in the 3 month period between March and the end of May (441 mm) far exceeding those in recent years, and with the river also experiencing very regular spates from October 2023. This high precipitation level is further emphasised by rainfall in the same period in 2025 only being 173 mm. Thus, once released into the main river channel in spring 2024, the tagged smolts were exposed to relatively high flows. These relatively high flows are important to consider given smolt emigration success has been recorded as varying both spatially and temporally, where the variability is a function of local environmental conditions (Rodger, Guthrie, et al. 2024). Indeed, low flow periods are recognised as an inhibitor of barrier passage in both upstream and downstream directions in anadromous fish generally (Bourne et al. 2011), as well as salmonid smolts more specifically (Enders et al. 2009; Marschall et al. 2011). For example, in the River Tweed, Scotland, salmonid smolts were delayed significantly longer at weirs in a year when flows were frequently below Q95, with migration success in a low flow year being as low as 19% (Gauld et al. 2013). Higher river flows are coincident with high river levels that often drown out weirs or at least reduce their head height, and thus result in conditions where downstream passage is less likely to be delayed or prevented (Gauld et al. 2013).

Downstream smolt movements can be largely passive as move with the river current (Hansen et al. 1984), although more active movement downstream has also been suggested (Fångstam 1993; Aarestrup and Koed 2003). Where movement is largely passive then this emphasises the importance of periods of elevated river flows and levels as these provide more favourable conditions for such passive movements. While rapid salmonid smolt emigrations have been detected in some systems (e.g., < 3 days to move 52 km and with downstream movement speeds recorded to 65 km per day; Chaput et al. 2019), migrations times can also be more prolonged, lasting weeks or even months (Bohlin et al. 1993; Thorstad et al. 2011; Rodger, Guthrie, et al. 2024). Here, perhaps due to the elevated river flows and levels, migration was generally fast, with the first detection in the lower river generally being within 4 days of leaving the upper river—and less than 2 days in some fish—with speed of downstream movement recorded to over 23 km per day. This is relatively fast compared to other

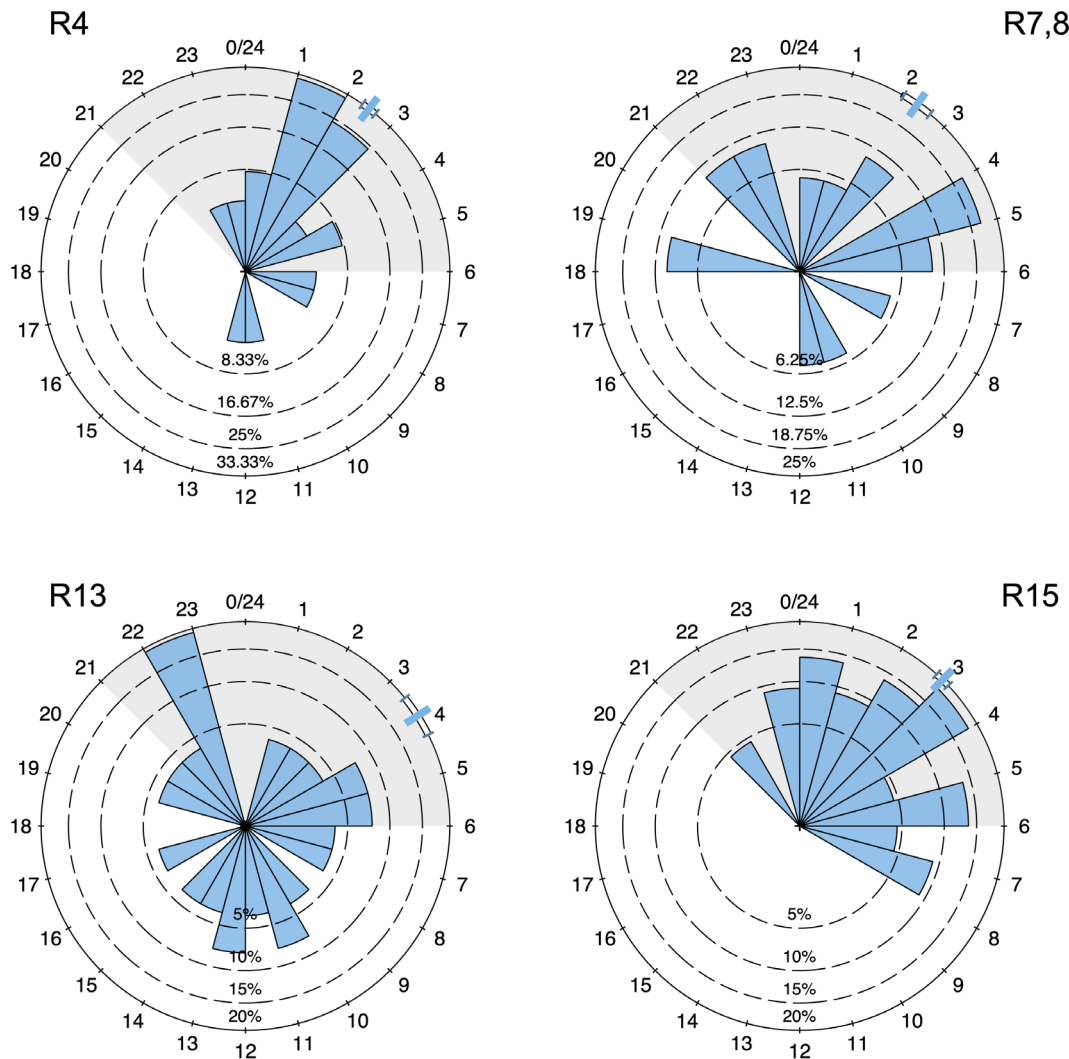


FIGURE 4 | Times of arrival by smolts (combined by species) at the four main receiver locations with detections (Table 1), where the small blue bar on the outer circle indicating the mean time of arrival and the respective ranges showing the standard error of the mean. Each group's bars sum to 100%, and the shaded grey areas represent nocturnal hours. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rm.70144)]

British rivers (only one of 24 rivers had smolts emigrating at faster speeds in Rodger, Guthrie, et al. 2024). However, in the River Frome, a chalk stream in southern England, trout smolts can move as much as 60km per day (Thorstad et al. 2011; Lauridsen et al. 2017). In considering the relatively fast speed of movement downstream in our study, it is again emphasised that this was a high flow year in a spate river of high velocity. It was also considered that the tagged smolts were highly motivated to emigrate (McCormick et al. 1998). This is because the smolts had been captured from an off-channel diversion where they were considered as entrained (albeit with no information on their prior movement and migration history), tagged and then released into the main river channel downstream of the diversion intake. These tagged smolts were thus considered as having high motivation to move downstream quickly due to their capture being relatively late in the smolt run and that they had potentially been entrained in the diversion for some days (McCormick et al. 1998).

The receiver efficiencies in the study were highly variable, with it acknowledged that a study limitation was the zero

detections of the tagged smolts in the vicinity of their release site. This negligible detection rate was considered to be a function of the interaction of the acoustic transmitters not being programmed to pulse regularly enough (60s) in a relatively fast-moving fish to be detected on receivers of limited detection ranges (approximately 40m). Future acoustic telemetry studies on this river should use transmitters with a more rapid pulse rate. The weather conditions of spring 2024 meant receiver deployment had to be completed in between frequent periods of elevated water level than provided very brief windows of opportunity to deploy (<1 day) and so receivers were deployed without range testing—contrary to best practice (Kessel et al. 2014). Moreover, receiver detection ranges are rarely fixed and instead change as environmental conditions alter (Winter et al. 2021). Consequently, even had range testing been completed in low flow conditions, it is likely that the elevated water levels that triggered the smolt migrations would have provided noisier conditions that reduced the detection range. Nevertheless, there were receivers that did provide sufficient detections in four strategic locations that did enable the migration success of the tagged smolts to be determined.

Most, but not all, smolt detections occurred in the hours of darkness, with smolt movements generally being nocturnal in both salmon and trout smolts (Aarestrup et al. 2002; Flávio et al. 2020; Lauridsen et al. 2017). This is considered a behavioural adaptation that limits exposure to visual predators, with movements in the hours of light often more apparent with increases in both distance downstream and time since the start of the overall smolt migration run (Ibbotson et al. 2006; Flávio et al. 2020). The exception here to the smolts mainly being detected in the hours of darkness was at R13, where some smolts were detected in daylight, presumably as they paused their movement downstream before resuming again at dark (R13 was located just upstream of a barrier).

These smolts were from a population in a moorland-fed river of southwest England, whose population is predicted to persist throughout the century, whereas many other populations across Britain are predicted to decline due to climate change, with predicted extirpation of most populations in southern England (Ruiz-Navarro et al. 2016b). These populations are thus important in conservation terms. These smolts, captured from a hydropower off-channel diversion and then released into the adjacent river, revealed relatively high migration success compared to some rivers, although further work is needed in migration periods of lower flows to identify whether such migration success rates are typical in all years or just during spring periods characterised by high river levels and flows. In this period of high flows, weirs and hydropower schemes did not appear to impede the downstream movements of the smolts in a major way. However, work in 2025 has suggested that salmon smolts entrained into off-channel diversions can be impeded from successfully migrating downstream (unpublished data, the Authors). In combination with the results here, it thus suggests that using the capture of entrained smolts and their release into the main river channel can be successful as a mitigation against the potentially harmful effects of entrainment in off-channel hydropower diversions, so increasing the number of smolts successfully completing their riverine migrations.

Acknowledgments

B.I.C.W. was funded through a studentship partnership between Bournemouth University, Environment Agency, the Teign Anglers Conservation Association and the West Country Rivers Trust. We thank access permissions granted from the National Trust, Teign Anglers Conservation Association and the Newton Abbot Fishing Association during fieldwork. We especially thank Geoff Stephens for all his help in organising access to site and receiver locations, and assistance with electric fishing. We also acknowledge the help of Tom Major for his fieldwork assistance.

Funding

B.I.C.W. was funded through a studentship partnership between Bournemouth University, Environment Agency, the Teign Anglers Conservation Association and the West Country Rivers Trust.

Ethics Statement

All aspects of data collection were completed following ethical approval and were licenced under the U.K. Animals (Scientific Procedures) Act (1986) (project licence number: PPL PA2C7C4E6).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

- Aarestrup, K., and A. Koed. 2003. "Survival of Migrating Sea Trout (*Salmo trutta*) and Atlantic Salmon (*Salmo salar*) Smolts Negotiating Weirs in Small Danish Rivers." *Ecology of Freshwater Fish* 12, no. 3: 169–176.
- Aarestrup, K., C. Nielsen, and A. Koed. 2002. "Net Ground Speed of Downstream Migrating Radio-Tagged Atlantic Salmon (*Salmo salar*) and Brown Trout (*Salmo trutta*) Smolts in Relation to Environmental Factors." In *Aquatic Telemetry: Proceedings of the Fourth Conference on Fish Telemetry in Europe*, 95–102. Springer Netherlands.
- Birnie-Gauvin, K., M. M. Candee, H. Baktoft, M. H. Larsen, A. Koed, and K. Aarestrup. 2018. "River Connectivity Reestablished: Effects and Implications of Six Weir Removals on Brown Trout Smolt Migration." *River Research and Applications* 34, no. 6: 548–554.
- Bohlin, T., C. Dellefors, and U. Faremo. 1993. "Optimal Time and Size for Smolt Migration in Wild Sea Trout (*Salmo trutta*)." *Canadian Journal of Fisheries and Aquatic Sciences* 50, no. 2: 224–232.
- Boubée, J. A. T., and E. K. Williams. 2006. "Downstream Passage of Silver Eels at a Small Hydroelectric Facility." *Fisheries Management and Ecology* 13, no. 3: 165–176.
- Bourne, C. M., D. G. Kehler, Y. F. Wiersma, and D. Cote. 2011. "Barriers to Fish Passage and Barriers to Fish Passage Assessments: The Impact of Assessment Methods and Assumptions on Barrier Identification and Quantification of Watershed Connectivity." *Aquatic Ecology* 45: 389–403.
- Chapman, B. B., A. Eriksen, H. Baktoft, et al. 2013. "A Foraging Cost of Migration for a Partially Migratory Cyprinid Fish." *PLoS One* 8, no. 5: e61223.
- Chaput, G., J. Carr, J. Daniels, S. Tinker, I. Jonsen, and F. Whoriskey. 2019. "Atlantic Salmon (*Salmo salar*) Smolt and Early Post-Smolt Migration and Survival Inferred From Multi-Year and Multi-Stock Acoustic Telemetry Studies in the Gulf of St. Lawrence, Northwest Atlantic." *ICES Journal of Marine Science* 76, no. 4: 1107–1121.
- Colvin, M. E., J. T. Peterson, C. Sharpe, M. L. Kent, and C. B. Schreck. 2018. "Identifying Optimal Hauling Densities for Adult Chinook Salmon Trap and Haul Operations." *River Research and Applications* 34, no. 9: 1158–1167.
- Department for Environment, Food and Rural Affairs. 2025. "Mardon Down." <https://environment.data.gov.uk/hydrology/station/323b21d8-c9a4-4681-bc5c-62d7337993ac>.
- Enders, E. C., M. H. Gessel, and J. G. Williams. 2009. "Development of Successful Fish Passage Structures for Downstream Migrants Requires Knowledge of Their Behavioural Response to Accelerating Flow." *Canadian Journal of Fisheries and Aquatic Sciences* 66, no. 12: 2109–2117.
- Environment Agency. 2024a. "Hydrology Station Data Viewer." <https://environment.data.gov.uk/hydrology/station/323b21d8-c9a4-4681-bc5c-62d7337993ac>.
- Environment Agency. 2024b. "Salmonid and Freshwater Fisheries Statistics for 2023." <https://www.gov.uk/government/publications/salmonid-and-freshwater-fisheries-statistics-2023/salmonid-and-freshwater-fisheries-statistics-for-2023>.

- Fängstam, H. 1993. "Individual Downstream Swimming Speed During the Natural Smolting Period Among Young of Baltic Salmon (*Salmo salar*)."
Canadian Journal of Zoology 71, no. 9: 1782–1786.
- Flávio, H., H. Baktoft, and E. Codling. 2021. "Actel: Standardised Analysis of Acoustic Telemetry Data From Animals Moving Through Receiver Arrays."
Methods in Ecology and Evolution 12, no. 1: 196–203.
- Flávio, H., R. Kennedy, D. Ensing, N. Jepsen, and K. Aarestrup. 2020. "Marine Mortality in the River? Atlantic Salmon Smolts Under High Predation Pressure in the Last Kilometres of a River Monitored for Stock Assessment."
Fisheries Management and Ecology 27, no. 1: 92–101.
- Gauld, N. R., R. N. B. Campbell, and M. C. Lucas. 2013. "Reduced Flow Impacts Salmonid Smolt Emigration in a River With Low-Head Weirs."
Science of the Total Environment 58: 435–443.
- Gibeau, P., B. M. Connors, and W. J. Palen. 2017. "Run-Of-River Hydropower and Salmonids: Potential Effects and Perspective on Future Research."
Canadian Journal of Fisheries and Aquatic Sciences 74, no. 7: 1135–1149.
- Gill, J. A., J. A. Alves, W. J. Sutherland, G. F. Appleton, P. M. Potts, and T. G. Gunnarsson. 2014. "Why Is Timing of Bird Migration Advancing When Individuals Are Not?"
Proceedings of the Royal Society B: Biological Sciences 281, no. 1774: 20132161.
- Graham, C. T., and C. Harrod. 2009. "Implications of Climate Change for the Fishes of the British Isles."
Journal of Fish Biology 74, no. 6: 1143–1205.
- Grill, G., B. Lehner, M. Thieme, et al. 2019. "Mapping the World's Free-Flowing Rivers."
Nature 569, no. 7755: 215–221.
- Hansen, L. P., B. Jonsson, and K. B. Døving. 1984. "Migration of Wild and Hatchery Reared Smolts of Atlantic Salmon, *Salmo salar* L., Through Lakes."
Journal of Fish Biology 25, no. 5: 617–623.
- Haraldstad, T., F. Kroglund, T. Kristensen, B. Jonsson, and T. O. Haugen. 2017. "Diel Migration Pattern of Atlantic Salmon (*Salmo salar*) and Sea Trout (*Salmo trutta*) Smolts: An Assessment of Environmental Cues."
Ecology of Freshwater Fish 26, no. 4: 541–551.
- Ibbotson, A. T., W. R. C. Beaumont, A. Pinder, S. Welton, and M. Ladle. 2006. "Diel Migration Patterns of Atlantic Salmon Smolts With Particular Reference to the Absence of Crepuscular Migration."
Ecology of Freshwater Fish 15, no. 4: 544–551.
- Jensen, A. J., O. H. Diserud, B. Finstad, P. Fiske, and E. B. Thorstad. 2022. "Early-Season Brown Trout (*Salmo trutta*) Migrants Grow and Survive Better at Sea."
Journal of Fish Biology 100, no. 6: 1419–1431.
- Jones, J., L. Börger, J. Tummers, et al. 2019. "A Comprehensive Assessment of Stream Fragmentation in Great Britain."
Science of the Total Environment 673: 756–762.
- Kessel, S. T., S. J. Cooke, M. R. Heupel, et al. 2014. "A Review of Detection Range Testing in Aquatic Passive Acoustic Telemetry Studies."
Reviews in Fish Biology and Fisheries 24: 199–218.
- Kock, T. J., J. W. Ferguson, M. L. Keefer, and C. B. Schreck. 2021. "Review of Trap-And-Haul for Managing Pacific Salmonids (*Oncorhynchus* s) in Impounded River Systems."
Reviews in Fish Biology and Fisheries 31, no. 1: 53–94.
- La Sorte, F. A., D. Fink, W. M. Hochachka, and S. Kelling. 2016. "Convergence of Broad-Scale Migration Strategies in Terrestrial Birds."
Proceedings of the Royal Society B: Biological Sciences 283, no. 1823: 20152588.
- Lauridsen, R. B., A. Moore, S. D. Gregory, W. R. C. Beaumont, L. Privitera, and J. A. Kavanagh. 2017. "Migration Behaviour and Loss Rate of Trout Smolts in the Transitional Zone Between Freshwater and Saltwater." In *Sea Trout: Science & Management*, 292–307. Matador by Troubador Publishing Ltd.
- Lok, T., O. Overdijk, and T. Piersma. 2015. "The Cost of Migration: Spoonbills Suffer Higher Mortality During Trans-Saharan Spring Migrations Only."
Biology Letters 11, no. 1: 20140944.
- Lusardi, R. A., and P. B. Moyle. 2017. "Two-Way Trap-And-Haul as a Conservation Strategy for Anadromous Salmonids."
Fisheries 42: 478–487.
- Marschall, E. A., M. E. Mather, D. L. Parrish, G. W. Allison, and J. R. McMenemy. 2011. "Migration Delays Caused by Anthropogenic Barriers: Modeling Dams, Temperature, and Success of Migrating Salmon Smolts."
Ecological Applications 21, no. 8: 3014–3031.
- McCormick, S. D., L. P. Hansen, T. P. Quinn, and R. L. Saunders. 1998. "Movement, Migration, and Smolting of Atlantic Salmon (*Salmo salar*)."
Canadian Journal of Fisheries and Aquatic Sciences 55, no. S1: 77–92.
- Meixler, M. S., M. B. Bain, and M. T. Walter. 2009. "Predicting Barrier Passage and Habitat Suitability for Migratory Fish Species."
Ecological Modelling 220, no. 20: 2782–2791.
- Mouritsen, H. 2018. "Long-Distance Navigation and Magnetoreception in Migratory Animals."
Nature 558, no. 7708: 50–59.
- Ohms, H. A., D. N. Chargualaf, G. Brooks, C. Hamilton, E. P. Palkovacs, and D. A. Boughton. 2022. "Poor Downstream Passage at a Dam Creates an Ecological Trap for Migratory Fish."
Canadian Journal of Fisheries and Aquatic Sciences 79, no. 12: 2204–2215.
- Otero, J., J. H. L'Abée-Lund, T. Castro-Santos, et al. 2014. "Basin-Scale Phenology and Effects of Climate Variability on Global Timing of Initial Seaward Migration of Atlantic Salmon (*Salmo salar*)."
Global Change Biology 20, no. 1: 61–75.
- R Core Team. 2024. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. <https://www.R-project.org/>.
- Rodger, J. R., J. Guthrie, H. M. Honkanen, et al. 2024. "Determinants of Riverine Migration Success by Atlantic Salmon (*Salmo salar*) Smolts From Rivers Across the UK and Ireland."
Journal of Fish Biology 106, no. 5: 1585–1600.
- Rodger, J. R., P. Kaiser-Wilks, S. V. Beck, J. C. Ribbens, A. J. Lothian, and C. E. Adams. 2025. "Downstream Migration Success of Atlantic Salmon Smolts in a River Catchment Highly Fragmented by Hydroelectric Impoundments."
Ecology of Freshwater Fish 34, no. 1: e12821.
- Rodger, J. R., J. Lilly, H. M. Honkanen, et al. 2024. "Inshore and Offshore Marine Migration Pathways of Atlantic Salmon Post-Smolts From Multiple Rivers in Scotland, England, Northern Ireland, and Ireland."
Journal of Fish Biology 106, no. 5: 1585–1600.
- Ruiz-Navarro, A., P. K. Gillingham, and J. R. Britton. 2016a. "Predicting Shifts in the Climate Space of Freshwater Fishes in Great Britain due to Climate Change."
Biological Conservation 203: 33–42.
- Ruiz-Navarro, A., P. K. Gillingham, and J. R. Britton. 2016b. "Shifts in the Climate Space of Temperate Cyprinid Fishes due to Climate Change Are Coupled With Altered Body Sizes and Growth Rates."
Global Change Biology 22, no. 9: 3221–3232.
- Schwinn, M., H. Baktoft, K. Aarestrup, M. C. Lucas, and A. Koed. 2018. "Telemetry Observations of Predation and Migration Behaviour of Brown Trout (*Salmo trutta*) Smolts Negotiating an Artificial Lake."
River Research and Applications 34, no. 8: 898–906.
- Sigourney, D. B., J. D. Zydlewski, E. Hughes, and O. Cox. 2015. "Transport, Dam Passage, and Size Selection of Adult Atlantic Salmon in the Penobscot River, Maine."
North American Journal of Fisheries Management 35: 1164–1176.
- Thorstad, E. B., I. Uglem, P. Arechavala-Lopez, F. Økland, and B. Finstad. 2011. "Low Survival of Hatchery-Released Atlantic Salmon Smolts During Initial River and Fjord Migration."
Boreal Environment Research 16, no. 2: 115.
- Thorup, K., A. P. Tøttrup, M. Willemoes, et al. 2017. "Resource Tracking Within and Across Continents in Long-Distance Bird Migrants."
Science Advances 3, no. 1: e1601360.
- Winter, E. R., A. M. Hindes, S. Lane, and J. R. Britton. 2021. "Detection Range and Efficiency of Acoustic Telemetry Receivers in a Connected Wetland System."
Hydrobiologia 848: 1825–1836.