Navigating complexity: channel selection of Atlantic salmon smolts through an island network during their migration to the marine environment

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**Abstract**

This study provides insights into the river channel pathways and migration rates of Atlantic salmon smolts migrating through a dynamic island channel network in the lower portion of a large river towards the marine environment. In 2022, 45 Atlantic salmon smolts were acoustically tagged in the Kedgwick River, a tributary of the Restigouche River, approximately 100 km upstream of the head of tide. Acoustic receivers were installed throughout an island network, preceding the estuary, to identify preferred smolt migration pathways and compare them to the locations of smolt traps that are used to estimate out-migrating smolt population abundance. Migration speeds from the release point in river to an oceanic acoustic array located in the Strait of Belle Isle (~1000 km) were calculated across habitat types revealing that in-river speeds (~50 km.day-1) were considerably faster relative to speeds in estuarine and oceanic habitats (~ 20 km.day-1). Most tagged fish exited the river uninterrupted, while a fraction of them spent hours to days lingering in the island network before entering the marine environment. Ultimately, this study revealed that a substantial proportion of smolts (15-60%) traveled through channels without smolt traps therefore avoiding the monitoring program at this location. This study quantifies the proportion of smolts using the various channels available to them and provides insights into why capture probabilities at the limited number of monitoring sites within the channel network are low.

# Introduction

The Atlantic salmon (*Salmo salar* L.) is a well-studied salmonid species that manifests a great variety of life history strategies including anadromy (Erkinaro et al. 2019). Wild Atlantic salmon population abundances have been in decline across their native range over the last few decades, with scientific consensus pointing to decreased survival at sea being largely responsible (Jonsson and Jonsson 2004; Chaput 2012; ICES 2021). While the exact mechanisms are not fully understood (Thorstad et al. 2021), the causes for this decline in at-sea survival have been linked to changes in both the freshwater (Armstrong 2005; Russell et al. 2012; Otero et al. 2014; Gregory et al. 2019) and marine (Beaugrand and Reid 2012; Mills et al. 2013; Friedland et al. 2014; Olmos et al. 2020; Harvey et al. 2022) phases of the lifecycle which lead to changes in a range of demographic parameters across populations at a broad spatial scale (Olmos et al. 2019, 2020).

Anadromous species engage in a form of diadromy (McDowall 2008; Delgado and Ruzzante 2020) characterized by the use freshwater habitats for spawning and juvenile rearing and the use of marine habitats for growth and maturation (Finstad et al. 2010; Thorstad et al. 2010), with adults returning to freshwater to spawn (Quinn and Myers 2004). Atlantic salmon juveniles spend several years living in freshwater as a parr before becoming a smolt and undergoing the morphological, physiological and behavioral changes required to cope with the transition to the marine environment (i.e., smoltification; McCormick et al. 1998; Jonsson and Jonsson 2003; Mobley et al. 2021).

The smoltification process enables them to cope with changes in salinity, thermal regimes, and predators, and synchronizing their migration with favorable feeding conditions in the ocean (Hansen and Quinn 1998; McCormick et al. 1998; Friedland et al. 2003; Jonsson and Jonsson 2004). Prior to entering the marine environment, smolts will often spend several days (Prunet and Boeuf 1985; Kocik et al. 2009) at the interface between fresh and marine water to allow them to undergo the physiological changes needed to increase their tolerance to increased salinity (Hoar 1988; McCormick et al. 2013) and adapt to their new habitat. Successful transition from freshwater to marine environments is critical for maintaining healthy salmon populations, and it marks the first step of the smolt-to-returning adult survival and is a determining factor in the eventual recruitment of adult salmon returning to freshwater habitats for spawning (Russell et al. 2012).

The downstream migration of Atlantic salmon smolts is predictable (e.g., Dauphin et al. 2023). Migration towards estuarine waters occurs in spring and is influenced by multiple factors. Key triggers include day length, water temperature, and river flow, which collectively initiate migratory behavior (McCormick et al. 1998). Most individuals migrate within a narrow one-to-two-week time window (Thorstad et al. 2012), usually travelling at night following the river’s main current (McCormick et al. 1998).

The Restigouche River catchment (New Brunswick/Quebec, Canada) hosts a large Atlantic salmon population (Dauphin 2022, DFO, 2023) with various life stages, including smolts, having been monitored over several decades. Dauphin et al. (2023) demonstrated that the probabilities of capture at certain smolt traps (rotary screw traps, RSTs) sampling the entire population are low (i.e., a fraction of a percent) leading to large uncertainties in abundance estimates. The RSTs intended to sample the entire population are installed in two channels of a complex island network located near the head of tide. It is hypothesized that these low probabilities of capture may result from poor trap catchability within the monitored channel and/or a considerable proportion of smolts migrating through channels without RSTs.

This study investigates the complexity of smolt migration dynamics of the Restigouche population, from the lotic to pelagic habitat with a focus on the area at the interface between fresh and salt water (i.e., island network). Through empirical observations and modeling techniques, we explore variations in migrations patterns, and migration delays, shedding some light on the intricacies of smolt behavior in this ecosystem. Moreover, we assess whether smolts navigating through this island network are swimming through channels where an RST is deployed which could explain low probability of capture at these traps therefore impacting the monitoring program.

# Material and Methods

## Study site and data collection

Smolt abundance has been monitored in the Restigouche River since 2002. Dauphin et al. (2023) details the data collection process thoroughly, but its main features are described below. Each year, one to five RSTs are installed at the mouths of key tributaries and near the head of tide. Capture-mark-recapture (CMR) experiments are conducted at each RST to estimate tributary-specific or whole-river smolt abundances. The whole-river abundance is estimated using one or two RSTs installed in two river channels located within an island network (Figure 1). The locations of these RSTs were chosen in the early 2000s based on the dominant flows of the river in this area as well as the suitability of the riverbed profile to install an RST (i.e., thalweg deep enough to keep operating the RST throughout the smolt run as water level decreases; DFO, unpubl.).

The current study takes advantage of another experiment taking place in the Restigouche catchment involving the marking of 45 smolts with acoustic tags in the Kedgwick River in the spring of 2022 with the aim of assessing the timing of their migration and their survival at sea (Chaput et al. 2019). Additional receivers were strategically placed at key channel bifurcations amidst the island network where the downstream RSTs were installed to identify channel selection by smolts migrating throughout the island network.

In 2022, 45 Atlantic salmon smolts were captured and marked with acoustic tags in the Kedgwick River (Restigouche catchment, Canada; 115 km upstream of the head of tide) as part of an ongoing experiment to estimate smolt survival during their migration at sea. V8 Acoustic tags transmitting a unique identification code at 69 kHz (Innovasea Marine Systems Canada, Inc., Halifax, NS), were surgically implanted into the peritoneal cavity of selected smolts. Fish were held within in-river pens post-surgery for several hours prior to being released. Tags were programmed to ping at random intervals between 25 and 55 seconds and had an estimated minimum battery life of 74 days (see Chaput et al. 2019). Smolts were tagged on May 24th, 2022, and May 26th, 2022. Larger individuals were preferred to reduce the tagging burden and smolts used in the experiment had an average fork length of 145 mm (s.d.=8.3) and an average weight of 27 g (s.d.= 5.7, Table 1). This experiment used acoustic receivers (VR2W, VR2Tx, or VR2AR models, Innovasea Marine Systems Canada, Inc.) singly or arranged in arrays throughout their migration route from the release site to the Strait of Belle Isle (SoBI). For our experiment, nine additional acoustic receivers were installed in the lower part of the Restigouche River in order to identify channel selection preferences within the island network leading to the Restigouche estuary. Based on the environmental conditions of spring 2022 (mainly water level and flow), several paths through the island network were deemed navigable by out-migrating smolts (Figure 1). Due to the number of acoustic receivers deployed in the region, these individuals were tracked in-river, in the area of interest of our case-study (i.e., island network) and in the marine habitat up to the Strait of Belle Isle, North of Newfoundland, covering a distance of approximately 965 km.

## Modelling

A state-space model was developed to estimate and disentangle the probabilities of detection at the receivers and the probabilities of travel towards the various channels of the island network based on the detection history of the 45 smolts tagged in the Kedgwick River. All smolts were assumed to have survived as all tags were detected downstream of the island network. This is a critical hypothesis as the model could not run without this assumption being met. However, we are confident based on their detection patterns (Suppl. Mat A) that all smolts in this study survived up to their entry into the estuary. To keep the text concise, several indices are used throughout this section: *i* for individual fish, *r* for receivers, *z* for channel network zone, and *c* for channel (Table 2).

The detection status of a smolt *i* at a given receiver *r* is a binary variable denoted which takes the value 1 if a smolt is detected and 0 otherwise. At two locations (MM and HoT, Table 2), several receivers were installed to form an array and increase the probability of detection; at these locations, all detections from the receivers making the array were pooled. Therefore, for these two locations, the probability of detection corresponds to the joint probability of detection of several receivers.

It is assumed that smolts are only moving downstream (confirmed by data, Ibbotson et al. 2006; Thorstad et al. 2012). Based on this assumption and the navigation paths deemed available during the time of the experiment (Figure 1), the presence of a smolt in a given zone and channel can be expressed conditionally on its previous zone and channel location, and the probabilities to go towards the next zone and channels available.

Smolts travelling outside of the island network (*i.e.*, upstream of receiver Rx1 and downstream of receivers R3a and R3b at the HoT array) have only one channel available to them. Therefore, for receivers , the detection status is noted:

Eq. 1

Where is the probability of detection at receiver or array of receivers *r*.

The island network is divided in five zones *z* in which a smolt *i* can only be in one of two to four channels *c* per zone (Figure 1)*.* The presence of a smoltin a channelof a given zoneis a binary variable denoted which takes the value 1 if a smolt is in zone *z* and channel *c* and 0 otherwise. Prior to entering the first zone of the island network, smolts can only be in a single channel, thus, their presence in channel one of zone one is only conditional on the probability of traveling towards this channel, .

Eq. 2

Since a smolt can only be in one of the two channels, the presence of a smolt in the second channel of the first zone is the complement:

Eq. 3

The detection at either of the receivers in the first zone (R1a-b, , Table 2) is the product of the smolt’s presence in the channel and the probability of detection at the receiver *r:*

Eq. 4

For zones two to five, the presence of a smolt in a given channel is conditioned by the available paths allowed in the model (Figure 1). Unfortunately, acoustic receivers are not present in all channels and therefore the presence of a smolt in a given zone and channel cannot always be confirmed by detections (regardless of the imperfect detection rate of receivers). Smolts present in zone one and channel one () can travel in channel one of zone two (, where the Moses RST is installed) with a probability . Smolts present in zone one and channel two () can travel in channel three of zone two () with a probability while the rest of the smolts will travel towards the middle channel () which translates in the following equations:

Eq. 5

Eq.6

Eq. 7

There are two acoustic receivers in zone two, R2a and Rx2b (), and their detections are expressed as follows:

Eq. 8

Eq. 9

When travelling from zone two to three, certain paths are compulsory. For instance, smolts that were in channel one and three of zone two can only travel towards channels one and four of zone three, respectively.

Eq. 10

Eq.11

Smolts that were in channel two have a probability to travel towards the second channel of zone three. The rest of the smolts travel towards the third channel of zone three.

Eq. 12

Eq. 13

There is only one receiver zone 3, Rx2a (), and its detections are expressed as follows:

Eq. 14

Similarly to zone three, there are compulsory paths leading to channels in zone four, for instance smolts that are in channels one and two of zone three can only travel towards the first channel of zone four (Figure 1):

Eq. 15

Smolts that were in the fourth channel of zone three have a probability to travel towards the third channel of zone 4 (where the Butters RST is installed) and the rest of the smolts go through the second channel of zone four:

Eq. 16

Eq. 17

Similarly to the previous zone, there is only one receiver in zone four, R2b (), and its detections are expressed as follows:

Eq. 18

Smolts travelling to the fifth and final zone can navigate towards one of two channels. Smolts travelling to the second channel of zone five () can do so by travelling from the first and second channel of zone four (and ) with probabilities of travel and , respectively. Additionally, all smolts that were in channel three of zone four () will travel in the second channel of zone five. All other smolts from zone four travel to the other channel of zone five ().

Eq. 19

Eq. 20

In zone five, an acoustic receiver is installed in each channel, R3a-b (), and their detections are expressed as follows:

Eq. 21

Eq. 22

## Bayesian inference

The state-space model is implemented in a Bayesian framework using JAGS 4.3.1 (Plummer, 2017) called from the package R2jags (Su & Yajima, 2020) in R 4.3.3 (2022). Three chains were run with an initial burn-in of iterations and followed by an additional iterations from which one out 100 was kept to reduce autocorrelation. In total, iterations were used to summarize the posterior distributions of each variable of interest. Convergence was assessed using the Gelman-Rubin statistic (Gelman and Rubin 1992), and MCMC chains were inspected visually to ensure that good mixing was achieved. Weakly informative priors were assigned to all probabilities ( and ) to be estimated (van de Schoot et al. 2021), namely a Beta distribution with both shape parameters equal to one. The scripts and data necessary to run this analysis are available on the GitHub repository created for this project (Dauphin, 2024).

# Results

All 45 smolts tags were detected at least once at one of the river receivers (Rx1 to R3b, Figure 1, Table 2) and 44 of them were detected at the head of tide array (HoT, Table 2) suggesting that all marked fish survived this part of their migration. A number of smolts were detected further at the inner bay (n=33), outer bay (n=39) and SoBI arrays (n=27) (Table 1) suggesting that at least 87% of these individuals made their way out of the Mawipoqtapei (Chaleur Bay) and 60% to North of Newfoundland.

## Travel time from release sites to SoBI array and residence time in the island network

On average, smolts were detected 167 times from the time of their release in the Kedgwick River to their entry in the estuary (HoT array). When detected at a receiver, most smolts were only detected a handful of times at that receiver. However, several receivers had a much higher average number of detections per fish. For receivers Rx1 and Rx2b this higher number of detections was driven by two or three individuals that appeared to remain in the vicinity of the receiver for a prolonged period of time (Figure 2, Table 1). For the HoT array, the higher number of detections was more generalized and partly explainable by the larger number of receivers (three) as well as the location of this array (i.e., mixture zone between fresh and salt water) where smolt would be more likely to pause to complete their physiological transition to adapt to the marine environment (Prunet and Boeuf 1985; Kocik et al. 2009).

A total of 25 smolts tags were detected upstream of the island network (Rx1); on average it took 2.14 days (s.d. = 0.93 days) for these smolts to reach this point from their release site. Based on the time of first detection at Rx1, this corresponds to an average migration speed of 53.5 km.day-1. A total of 44 smolts tags were detected at the HoT array; on average it took 3.98 days (s.d. =1.83 days) to reach this point (based on the time of release and time of first detection) for a mean migration speed of 34.8 km.day-1). From the HoT to the inner bay, outer bay and SoBI arrays, it took on average 1.52 (24.1 km.day-1, n=33), 4.89 (24.4 km.day-1, n=39) and 35.28 (21.3 km.day-1, n=27) days, respectively for the smolts to reach these points (Table 1, Figure 3).

Most smolts (41/45) were detected at least once at a receiver installed in one of the channels in the island network. It was possible to calculate the travel time through the island network (i.e., last detection at Rx1, and first detection at R3a or R3b equivalent to a distance of about six km, Figure 1, Table 1) for 21 smolts (Figure 2). The average travel time was about 11 hours (s.d.=16.4 hours, an average migration speed of 65.4 km.day-1) however, unlike any other travelling time computed in this study, there was a high variability among these fish (Figure 3): ten fish travelled in less than 1.5 hours, nine fish took more than 14 hours to exit the network while the last two fish swam through the network between 3.5 and 5 hours. Most of the fish that took more than 14 hours to exit the network were detected at a single receiver for an extended period of time. Apart from two fish (Fish #61838 left during the following high tide in the middle of the day and fish #61851 left at night 3 days later), these fish waited for the next dusk to start moving again (last detection at either R3a or R3b, Figure 2).

From the raw detections, it was possible to identify 10 smolts swimming through a channel with an RST (two at the Moses RST, receiver R2a; eight at the Butters RST, receiver R2b, Table 1). Additionally, seven smolts were detected at the Rx2a receiver, suggesting that these fish ‘avoided’ both RSTs (Figure 1, Table 1).

## State-space model

The information contained in the data led to a significant updating of the prior distributions of most of the probabilities of detection and travel paths to be estimated (Suppl. Mat. B). Probabilities of detection at the different acoustic receivers varied between 7.2% (R1a) and 95.7% (HoT array, Figure 4, Suppl mat. Table B1). The probability of detection at R2a and Rx2a were estimated at about 29% and 68%, respectively, with large uncertainties (2.5th-97.5th interquantile range of 4-87% and 26-99%, respectively, Figure 4, Suppl mat. Table B1) highlighting that the data were not sufficient to exclude high or low probabilities of detection at these two receivers. Probabilities of travel ranged from 8% to 89% (Figure 5, Suppl mat. Table B1 ), two of these probabilities, and , displayed large uncertainties and the posterior distributions were seemingly not updated from the prior distributions (Suppl. Mat. B). These two probabilities of travel were associated with the two receivers with large uncertainties (R2a and Rx2a) indicating that at these two locations the data were not sufficient to disentangle probability of travel and probability of detection.

For these reasons, the model did not have great predictive power: prior to the modelling exercise (raw detection only), 17 smolts could be classified as travelling in a channel with or without an RST. Post Bayesian inference, seven additional fish (25% of smolt with no raw data supporting presence or absence in a channel with an RST) could be assigned to the channel with the Butters RST with a high probability (>80%, Figure 6), one fish (ID 61690, Figure 6) had a 73% likelihood of taking a path without an RST installed, and the rest of the smolts (20) had about a 50% chance of travelling a route using the channel in which the Moses RST was installed or a channel with no RST (Figure 6, Suppl. Mat. C).

# Discussion

In anadromous salmonid species, the transition from freshwater to marine environments is a critical phase of their lifecycles marked by significant behavioral, morphological, and physiological changes. During this period, smolts must also adapt to new predators and environmental conditions, which collectively contribute to high mortality rates (Klemetsen et al. 2003; Thorstad et al. 2010).

The Restigouche River is of particular interest as it is one of two large rivers in the southern Gulf of St. Lawrence that supports a substantial Atlantic salmon population (Dauphin 2022; DFO 2023). The Restigouche River is also an index river where different life stages of the Atlantic salmon population have been monitored for decades for collaborative research and stock assessment purposes (Chaput et al. 2019; Dauphin et al. 2021, 2023). Our study emerged in this context and aims to address challenges encountered in the smolt monitoring program. Historical locations of the RSTs were chosen based on empirical assessment of flow in the network of island with the assumption that smolts were migrating using dominating currents (Moore et al. 1995) however, the RSTs installed in the network of islands and used in CMR experiments were found to have low catchabilities (i.e., often less than one percent) leading to uncertain estimates of the smolt population (Dauphin et al. 2023). These results raised important questions about the reasons for the low catchability rates. Do smolts migrating through the island network of islands avoid the channels where RSTs are installed, exhibit behaviors that lead to trap avoidance or are RSTs themselves less effective in this area?

First, we looked at smolt behavior by investigating the migration speed throughout the migration route of 45 smolts tagged in the Kedgwick River (a tributary of the Restigouche River). We found that the migration speed in the lotic habitat (i.e., from the release site to upstream of the island network – about 100 km) was 53.5 km.day-1, on the high end of what is reported in the literature (Thorstad et al. 2012), while migration speed in the oceanic habitat was much slower, ranging from 21.3 to 24.4 km.day-1 depending on where the migration speeds were measured. Interestingly, we found that the migration speed across our case-study site, the island network located near the Head of tide of the Restigouche River at the interface between the lotic and oceanic habitat, was highly variable with migration speeds ranging from 2.0 to 139.4 km.day-1.

All smolts in this study were tagged within a 48-hour period (24th-26th May) and were detected between one and five days later at the receiver upstream of the island network. First detections at the HoT array, about 120 km downstream from the release site, occurred between two- and nine-days post release. Finally, 26 of 27 fish detected at the SoBI array, about 1000 km from the release site, arrived within an eight-day window (June 29-July 6) with the last fish arriving 14 days later (July 21). This suggests that the highly variable smolt behavior in the earlier part of the migration i.e., halt of seaward migration to adapt to salt water may be compensated during the oceanic part of the migration leading to most smolts arriving in a relatively short time windows after almost 1000 km of migration.

The high variability in migration speed in the estuary was driven by a large number of smolts seemingly pausing for several hours before resuming their migratory behavior. Due to the number of receivers/arrays covering a large portion the migration route (i.e., about 965 km from the release site to the SoBI arrays) of Atlantic salmon smolts from the Restigouche River, it was possible to rule out predation up to the HoT array thus confirming that the prolonged stay in given areas corresponded to genuine behavior of smolts (#61835, #61836, #61841, Suppl. Mat. A). In the island network, the delays were generally approximately one day except for one individual that had paused for three days. Apart from movements of two smolts, migration after a pause was reinitiated after dusk. The predominantly nocturnal movements were similar to what was found in Moore et al. (1995) and the prolonged stay/interruption of the migration was similar to what was documented in other studies (Kocik et al. 2009; Dempson et al. 2011; Halfyard et al. 2013; Hawkes et al. 2017).

Second, we investigated the channel selection of the 45 marked individuals using a state-space model leveraging receiver deployments throughout the island network. Because we had confidence that smolts had survived to exit the river, we did not attempt to disentangle survival and detection probabilities, focusing rather on probabilities of movement through the channels of the island network and in particular to assess the proportion of individuals passing through a channel where an RST was deployed. Probabilities of detection and travel were estimated with various levels of uncertainty and in most cases the detection probabilities were above 50%. However, two receivers were found to have poor detection rates (i.e., R1a and R2a).

The poor detection rates in the island network can be explained by a number of environment and logistic factors associated to the fact that the Restigouche River is characterized as a highly dynamic gravel-bed river which is a challenging environment to use acoustic receivers. This is exacerbated in the island network where the variability in the riverbed topography and hardness can create acoustic shadows, echoes and obstacles that impede the transmission of acoustic signals (Enzenhofer and Cronkite 2000; Kessel et al. 2015; Lennox et al. 2023). The island network is located between the confluence of the Matapedia River with the Restigouche River and near the head of tide which results in daily fluctuations in water flow, turbulence, and sediment transport dynamics affecting the propagation of acoustic signals in the area (Kessel et al. 2015; Frechette et al. 2018). In this context, receiver deployment sites and array geometry can be suboptimal, leading to reduced detection efficiency and coverage. Finally, environmental noise, such as hydrodynamic noise from turbulent flow or anthropogenic activities (e.g., boat traffic), can interfere with acoustic signals and diminish receiver sensitivity (Kessel et al. 2015).

Despite sub-optimal receiver locations and detection rates, our study was able to identify that a non-negligible proportion of tagged smolts was not going through a channel where an RST was installed. Based solely on raw detections, at least 15 percent of the fish in this study avoided a channel with a trap. When accounting for fish with uncertain channel status, the maximum proportion of fish avoiding a channel with an RST could be higher than 60 percent. These results as well as the observed migration pausing behavior of a number of smolts support our hypotheses that a non-negligible proportion of smolts may avoid channels where an RST is installed which can contribute to the low catchabilities observed during CMR experiments (Dauphin et al. 2023).

While these results are compelling, they should be interpreted with caution when attempting to generalize them to the whole Restigouche River smolt population and across the time-series. First, because our sample size was relatively small, and due to the constraints associated with the size of acoustic tags, only larger fish were tagged. While we did not identify correlations between the size of the smolts and their migration speed and migration paths in the island network, this does not mean that it does not happen for smaller smolts. Second, all smolts were tagged and released within a 48-hour period towards the end of the smolt run in the Kedgwick River and, it is unknown if smolts migrating earlier in the season would display the same behaviors and associated variance. Finally, the island network is a very dynamic ecosystem subject to seasonal and annual variations meaning that our results might be applicable only to the year during which the experiment took place.

Ideally, this experiment will be repeated in future years with more smolts tagged across the full duration of the smolt-run and throughout the different tributaries of the Restigouche River with an enhanced receiver array geometry and associated range testing. These improvements would allow for a more comprehensive assessment of potential synchrony and behavioral patterns in smolt migration. Additionally, monitoring environmental covariates (e.g., discharge metrics) at the different branching points within the island network could improve our understanding of the probabilities of travel towards a given channel.

Our study has highlighted the challenges faced by the current smolt monitoring program and its CMR experiments due to the locations where the RSTs are deployed. Given the dynamic nature of a large system like the Restigouche River and the presence of anthropogenic activities (e.g. boating), identifying ideal sites for RST deployment remains complex. However, efforts should focus on exploring alternative locations upstream or downstream of the island network and/or enhance trap efficiency to effectively monitor the whole-river smolt outmigration.

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# Conflict of interest

None declared.

# Data Availabilty

All data and code required to reproduce the analysis presented in this article can be found in table 1 and the github repository https://github.com/guillaumed83/2022\_smolt\_movemen

# Ethics Statement

Smolt collection occurred as part of long-term monitoring programs conducted by Fisheries and Oceans Canada and tagging protocol was approved under Fisheries and Oceans Canada’s permit SG-RHQ-22-011.

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# Tables

Table 1: Summary of individual smolt biological characteristics and number of detections at each receiver or array of receivers and various travel. Column shading represents the different zones used in the state-space model.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Biological characteristics | | | Number of Detections | | | | | | | | | | | | | | | | Time from release to (days) | | Time from last detection HoT to (days) | | |
| Smolt ID | FL (mm) | Weight (g) | RP1 | MM1-2 | Rx1 | R1a | R1b | R2a | Rx2a | Rx2b | R2b | R3a | R3b | HoT | Inner Bay | Outer Bay | SoBI | Total | First detection at Rx1 | First detection at HoT | First detection at Inner Bay | First detection at Outer Bay | First detection at SoBI |
| 61690 | 147 | 27.4 | 1 | 19 | 203 | - | 1 | - | - | - | - | - | - | 7 | 3 | 9 | - | 243 | 1.38 | 3.56 | 1.03 | 3.94 | - |
| 61691 | 145 | 25.4 | 1 | 25 | 27 | - | 1 | - | - | 1 | - | - | 2 | 15 | - | 27 | 65 | 164 | 1.55 | 3.95 | - | 6.29 | 34.70 |
| 61692 | 145 | 26.1 | 1 | 18 | 1 | - | - | - | - | - | - | 1 | - | 24 | 5 | 5 | - | 55 | 2.07 | 2.52 | 1.47 | 3.26 | - |
| 61693 | 162 | 35.7 | 1 | 3 | 1 | - | - | - | - | - | - | 2 | - | 1 | - | - | 9 | 17 | 2.16 | 3.97 | - | - | 33.56 |
| 61834 | 146 | 25.6 | 1 | 10 | 1 | - | 2 | - | - | 1 | - | - | - | 24 | - | 3 | 8 | 50 | 1.43 | 3.62 | - | 5.46 | 32.83 |
| 61835 | 139 | 21 | - | 10 | 4 | - | 7 | - | 3 | - | - | 3 | - | 18 | 9 | 143 | 2 | 199 | 1.35 | 3.98 | 1.15 | 3.62 | 37.05 |
| 61836 | 163 | 42.5 | 1 | 3 | - | - | - | - | - | - | - | 1 | - | 69 | - | 20 | 12 | 106 | - | 5.32 | - | 4.74 | 31.57 |
| 61837 | 132 | 20.8 | 1 | 6 | 1 | - | 3 | - | - | 4 | 1 | - | 2 | 13 | 9 | 8 | 2 | 50 | 2.26 | 3.94 | 0.66 | 3.66 | 37.08 |
| 61838 | 148 | 28.9 | 1 | 7 | 1 | - | 8 | - | - | 9 | - | - | 28 | 44 | - | 8 | - | 106 | 2.26 | 4.41 | - | 4.66 | - |
| 61839 | 147 | 26.1 | - | - | - | 4 | - | - | - | - | - | 1 | - | 584 | 5 | 14 | 2 | 610 | - | 7.25 | 0.60 | 4.30 | 30.42 |
| 61840 | 142 | 25.8 | - | 5 | 1 | - | - | - | - | - | - | - | - | 16 | 36 | - | - | 58 | 3.73 | 3.97 | 0.69 | - | - |
| 61841 | 130 | 19.9 | 1 | 4 | 1 | - | 1 | - | - | 2 | 1 | - | 2 | 445 | 29 | 15 | 16 | 517 | 2.26 | 5.32 | 2.51 | 4.71 | 30.60 |
| 61842 | 149 | 26.7 | - | - | - | - | - | - | - | - | - | 1 | - | 90 | 1 | 71 | 4 | 167 | - | 7.25 | 1.18 | 6.10 | 30.34 |
| 61843 | 157 | 34.7 | - | - | - | - | - | - | 1 | - | - | - | - | 16 | 5 | 35 | 7 | 64 | - | 9.55 | 0.62 | 4.07 | 31.35 |
| 61844 | 134 | 19 | 1 | 14 | 3 | - | - | - | - | - | - | 1 | - | 19 | 9 | 13 | - | 60 | 2.42 | 7.07 | 1.80 | 10.15 | - |
| 61845 | 145 | 27.5 | 1 | 9 | 4 | - | 8 | - | - | 127 | - | - | 2 | 23 | 113 | 14 | 6 | 307 | 1.38 | 2.55 | 1.21 | 3.26 | 39.25 |
| 61846 | 159 | 35.7 | - | 2 | 1 | - | 1 | - | - | 4 | 1 | - | - | 639 | 2 | 1 | 7 | 658 | 3.64 | 4.37 | 1.48 | 3.36 | 31.49 |
| 61847 | 143 | 26 | 1 | 2 | - | - | 2 | - | - | 3 | 1 | - | - | 611 | - | 154 | 1 | 775 | - | 4.29 | - | 3.85 | 36.50 |
| 61848 | 140 | 26.9 | - | 6 | - | - | - | - | - | - | - | 1 | - | 10 | 2 | 27 | - | 46 | - | 2.10 | 1.01 | 9.29 | - |
| 61849 | 143 | 28.1 | 1 | 6 | 1 | - | 5 | - | - | 8 | 2 | - | 3 | 11 | 16 | - | 15 | 68 | 1.65 | 2.18 | 1.41 | - | 38.58 |
| 61850 | 141 | 24.1 | - | 1 | 1 | - | - | - | - | - | - | 1 | - | 9 | 1 | 4 | - | 17 | 1.66 | 2.24 | 1.54 | 3.76 | - |
| 61851 | 147 | 21.1 | - | - | 1 | - | - | 1 | - | - | - | 2 | - | - | - | - | - | 4 | 5.38 | - | - | - | - |
| 61852 | 138 | 21.5 | - | 3 | - | - | - | - | 1 | - | - | - | - | 75 | - | 17 | - | 96 | - | 1.90 | - | 4.92 | - |
| 61853 | 141 | 21.8 | 1 | 3 | - | - | 3 | - | 1 | - | - | - | - | 57 | 6 | 190 | - | 261 | - | 5.34 | 1.33 | 5.87 | - |
| 61854 | 134 | 20.4 | - | 3 | - | - | 4 | - | - | 1 | - | - | 1 | 57 | 27 | 228 | - | 321 | - | 2.29 | 1.08 | 3.92 | - |
| 61855 | 162 | 41.2 | - | 3 | - | - | - | - | - | - | - | 2 | - | 192 | - | 11 | 1 | 209 | - | 6.31 | - | 4.47 | 32.57 |
| 61856 | 147 | 29.5 | - | 3 | - | - | - | - | - | - | - | 1 | - | 7 | - | 29 | - | 40 | - | 2.12 | - | 4.91 | - |
| 61857 | 147 | 26 | 1 | 3 | - | - | 3 | - | - | 2 | 1 | - | - | 230 | 11 | - | - | 251 | - | 2.27 | 9.33 | - | - |
| 61858 | 135 | 19.3 | - | - | - | - | - | - | - | - | - | - | - | 5 | - | 26 | - | 31 | - | 2.86 | - | 5.47 | - |
| 61859 | 160 | 37.3 | - | 5 | - | - | - | - | - | - | - | - | - | 9 | 2 | 19 | - | 35 | - | 2.24 | 1.38 | 4.00 | - |
| 61860 | 155 | 31.3 | - | - | - | - | - | - | - | - | - | - | - | 144 | 23 | 52 | - | 219 | - | 7.35 | 1.52 | 6.89 | - |
| 61861 | 140 | 24.2 | - | - | - | - | - | - | - | 1 | - | - | - | 22 | 12 | 12 | 17 | 64 | - | 2.25 | 1.01 | 4.92 | 53.30 |
| 61870 | 145 | 25.3 | - | 3 | - | - | - | - | - | 1 | - | - | - | 7 | 11 | - | - | 22 | - | 2.77 | 0.82 | - | - |
| 61898 | 149 | 27.8 | 2 | 10 | 2 | - | 8 | - | - | 217 | 2 | - | 1 | 11 | 1 | 311 | - | 565 | 1.42 | 3.90 | 1.74 | 6.29 | - |
| 61899 | 141 | 23.9 | 1 | 11 | 2 | - | - | - | - | - | - | 1 | - | 581 | 14 | 2 | 6 | 618 | 2.37 | 7.77 | 1.03 | 4.53 | 31.21 |
| 61900 | 160 | 36.7 | 1 | 11 | 828 | - | - | - | - | - | - | 1 | - | 20 | 10 | 2 | 10 | 883 | 1.41 | 2.38 | 1.33 | 3.73 | 33.48 |
| 61901 | 141 | 23.2 | - | 4 | 1 | - | - | - | - | - | - | 2 | - | 1 | 7 | 16 | 1 | 32 | 2.17 | 3.54 | 1.97 | 4.46 | 36.32 |
| 61902 | 139 | 23.3 | 1 | 13 | 3 | - | - | - | - | - | - | 1 | - | 23 | 2 | 9 | 6 | 58 | 1.38 | 2.42 | 1.11 | 3.30 | 39.73 |
| 61903 | 148 | 23.7 | 1 | 1 | - | - | - | - | 3 | - | - | 2 | - | 14 | - | 23 | 2 | 46 | - | 3.90 | - | 5.27 | 35.97 |
| 61904 | 137 | 22 | - | 12 | 194 | - | - | 2 | - | - | - | 5 | - | 50 | 1 | 9 | 26 | 299 | 2.28 | 3.70 | 0.71 | 3.24 | 34.71 |
| 61905 | 141 | 22 | 1 | 12 | - | - | - | - | - | - | - | 3 | - | 7 | 4 | 9 | 2 | 38 | - | 3.47 | 1.02 | 3.69 | 37.95 |
| 61906 | 140 | 24.2 | 1 | 2 | 2 | - | - | - | 2 | - | - | 2 | - | 9 | 2 | 3 | 3 | 26 | 2.20 | 3.60 | 1.83 | 3.99 | 37.13 |
| 61907 | 146 | 26.9 | - | 4 | 2 | - | - | - | - | - | - | 2 | - | 9 | 6 | 7 | 7 | 37 | 2.18 | 3.05 | 0.97 | 3.45 | 35.99 |
| 61908 | 145 | 25.2 | - | 14 | 3 | - | 6 | - | - | 10 | 2 | - | 5 | 735 | 3 | 16 | 8 | 802 | 1.42 | 2.56 | 1.64 | 4.04 | 32.32 |
| 61909 | 152 | 31.5 | 1 | 2 | - | - | - | - | 1 | - | - | 1 | - | 411 | 2 | 28 | 5 | 451 | - | 3.72 | 1.84 | 7.04 | 36.50 |
| Avg detection/travel time |  |  | 1.0 | 7.2 | 51.6 | 4.0 | 3.9 | 1.5 | 1.7 | 26.1 | 1.4 | 1.7 | 5.1 | 121.9 | 11.8 | 40.8 | 9.3 | 216.6 | 2.14 | 3.98 | 1.52 | 4.79 | 35.28 |
| s.d. detection/travel time |  |  | 0.2 | 5.7 | 170.6 | - | 2.7 | 0.7 | 1.0 | 61.7 | 0.5 | 1.0 | 8.7 | 207.9 | 20.2 | 68.9 | 12.6 | 244.5 | 0.93 | 1.83 | 1.47 | 1.55 | 4.61 |

Table 2: Index summary for each receiver and number of individual tags detected at least once used in the state-space model. Receivers are listed from the most upstream (RP1) to the most downstream (HoT).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Receiver name | Receiver index *r* | Zone index *z* | Channel index *c* | Number of tags detected |
| RP1 | 1 | - | - | 23 |
| MM1-2 | 2 | - | - | 38 |
| Rx1 | 3 | - | - | 25 |
| R1a | 4 | 1 | 1 | 1 |
| R1b | 5 | 1 | 2 | 16 |
| R2a | 6 | 2 | 1 | 2 |
| Rx2b | 7 | 2 | 3 | 15 |
| Rx2a | 8 | 3 | 2 | 7 |
| R2b | 9 | 4 | 3 | 8 |
| R3a | 10 | 5 | 1 | 22 |
| R3b | 11 | 5 | 2 | 9 |
| HoT | 12 | - | - | 44 |

# Figures

A map of the pacific ocean

Description automatically generated

Figure 1: Panel A: Map of Northeast Canada, with highlighted Restigouche River catchment (in green) and the various receivers used in the study (colored dots). Panel B, Satellite image (16 Sept. 2021, Google Earth) of the island network in the Lower Restigouche. Numbered white squares represent the receivers installed during the 2022 experiment in this area. The orange dashed lines indicate the paths that were deemed navigable by out-migrating smolts at the time of the experiment. The blue colored polygons indicate the different zones and channels that a smolt could select and swim through during its downstream migration. The numbered yellow circles indicate the channels available in each zone; within a zone, a smolt can only be in one of the channels per zone. The symbols indicate the location of the RSTs installed in the island network as part of the annual smolt monitoring program. Panel C, Schematic representation of the network of paths usable by smolts. The arrows’ lengths are not proportional to distance, but arrows’ widths are proportional to the mean probability of a smolt to be in a given channel of a given zone (mean ± s.d. above the arrow) based on posterior distribution of the state-space model parameters. The sum of all channel probabilities of a given zone sometimes does not add up to one due to rounding error.

A screenshot of a graph

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Figure 2. Graphical representation of time of arrival and departure of smolts in the island network (delimited by Rx1 and R3a-b receivers) in the context of the diurnal (light and dark grey areas) and tidal cycles (blue line). Each horizontal segment traces an individual smolt, the left and right square indicate the time it was detected for the first time at Rx1 and the last time it was detected at R3a or R3b, respectively. The colour of the segment (green, orange and red) is used as a qualitative indicator of how long the journey through the island network took (less than 100 min, between 100 min and 8 hours and more than 8 hours, respectively). Tide (station Campbellton – 02175) and sunset (Campbellton - 48°0.9315 N 66°40.3582 W) data extracted from Canadian Services

A graph of different colored lines

Description automatically generated

Figure 3. Migration speed (km.day-1) of tagged Atlantic salmon smolts in 2022, measured between locations along their migration route (x-axis) to the SoBI array. The x-axis has a non-linear scale, with distances between locations shown below. Each sigmoidal polygon spans the segment where migration speed was computed, with the right edge indicating the mean migration speed ± s.d. (colored dots with vertical segments). Individual migration speeds (grey points) and sample sizes are also plotted on the right side. Different shades of grey in the background of the plot highlight habitat types (lotic, pelagic, and the island network).

A graph of a graph showing the same number of numbers

Description automatically generated with medium confidence

Figure 4. Probability of detection at each of the receivers installed in 2022, displayed left to right from the most upstream to most downstream. The coloured backgrounds indicate if the receiver is inside (shades of blue) or outside (white) of the island network and the different zones. The dots, and thick and thin vertical segments represent the median, and the 25th-75th and 2.5th-97.5th interquantile range of the posterior distributions. The grey area and red point and segments correspond to the prior distribution (Beta(1,1)) assigned to all probabilities of detection.

A graph of a number of travel distances

Description automatically generated with medium confidence

Figure 5. Probability of travel where z and c correspond to the zone (1 to 5) and the specific channel within that zone (1 to 4) where smoltsmay travel, respectively, displayed left to right from the most upstream to most downstream. In zone 5, there are two probabilities of travel towards the same channel estimated (and ). The coloured backgrounds indicate zone towards which the probability of travel is associated. The dots, and thick and thin vertical segments represent the median, and the 25th-75th and 2.5th-97.5th interquantile range of the posterior distributions. The grey area and red point and segments correspond to the prior distribution (Beta(1,1)) assigned to all probabilities of travel.

A graph of different colored lines

Description automatically generated with medium confidence

Figure 6. Probability of swimming through a channel with an RST (dark and light blue for Butters and Moses, respectively) or of taking a path that avoids both RSTs (light grey) for each of the 45 smolt tagged in 2022. Fish with 100% probability are fish that are detected at specific receivers leaving no doubt as to their location based on the allowed paths in the model (i.e. Moses channel if detected at R2a, Butters channel if detected at R2b, and avoiding RSTs if detected at Rx2a).