PIT Tracking River-Herring in the St. Croix Watershed
Anadromous Fish Assessments in 2023
Contract Number: P2400032

Introduction

River herring, a collective term for two closely related anadromous fish species; the alewife (*Alosa pseudoharengus*) and blueback herring (*Alosa aestivalis*) play a pivotal role in East coast river systems. They are considered a keystone species in aquatic food webs, deliver marine-derived nutrients to freshwater ecosystems, and provide a food source for many predators (Hare et al. 2021), creating a delicate yet robust web of interdependence. Many animals, ranging from predatory fish to an array of birds and mammals depend upon the seasonal migration of river herring from the ocean to freshwater for food. River herring also acts as a host species for freshwater mussel species and can act as a predation buffer for other anadromous fish species.

The East branch of the St. Croix River forms the international boundary between the United States and Canada, and the St. Croix watershed is the largest watershed between the Penobscot and the St. John drainages. Dam construction along the St. Croix's mainstem began in the early 1800's to control water flow for log driving and early industry. Today there are five dams currently spanning the river mainstem, with more dams and water control structures along tributaries. Annual river-herring counts at the Milltown Generating Station (MGS) began in 1981 following the construction of a new fishway. Significant declines in river herring counts at MGS were recorded after closures to upstream fishways located at the Vanceboro, Grand Falls, and Woodland dams between 1987 and 1995. Following the reopening of the Woodland fishway in 2008 and the Grand Falls fishway in 2013, river herring counts have increased at MGS, with 841,357 fish counted in 2023.

Currently MGS is undergoing decommissioning and removal, and restoration of the river at Salmon Falls is scheduled to be completed by April 2024. The information on fish passage collected prior to this removal holds significance in understanding the potential impacts on the broader riverine ecosystem. To monitor existing barriers to fish passage, the St. Croix International Waterway Commission, with support from the Passamaquoddy Recognition Group Inc. (PRGI), The Passamaquoddy Tribe at Indian Township – Wildlife Department, and the Sipayik Environmental Department (SED), used Passive Integrative Transponder (PIT) tags with accompanying detection equipment placed at five fishways within the St. Croix watershed to analyze the movement and passage efficiency of river herring. The data gathered provides insight into passage within these bottleneck points, return rates of river herring tagged in previous years, and estimates on the total number of fish potentially passing each dam by utilizing data from fish counts conducted at MGS.

Tagging and data collection efforts in the St. Croix began in 2017, with SED tagging river herring below MGS using cast nets. SED tagged 592 fish in 2018, with 27 fish tagged by the St. Croix International Waterway Commission (SCIWC) in Magurrewock Stream, a tributary to the St. Croix located in the Moosehorn National Wildlife Refuge, outside Calais, Maine. In 2019, SCIWC tagged a total of 465 river herring at the Magurrewock Stream fishway. In 2021, SCIWC in partnership with PRGI and the Passamaquoddy Tribe at Indian Township tagged a total of 503 fish at the MGS fish trap located near the fishway exit. Also in 2021, PRGI began PIT tagging as part of their Quoddy Region: River, Estuary, and

Coastal Restoration Plan, tagging 17 fish, which included river herring, American Eel, and American Shad in the St. Croix river basin, 174 river herring at the St. George dam located at the head of tide of the Magaguadavic River (Canada), and 127 river herring at Middle Lake dam located on Dennis Stream (Canada), which flows into the St. Croix estuary. In 2022, 525 river herring and 8 American shad were tagged at the MGS fishway.

Methods

Tagging

Tagging was staggered throughout the river herring upstream migration, beginning in early May, and ending in late June. The number of fish tagged per week increased with coincidingly increasing counts at Milltown, and tagging efforts decreased with decreasing counts (Table 1). The tagging process took place at the MGS fishway (Figure 1), utilizing a built-in screen gate to close off the trap exit. Fish were captured in small groups (3-4 fish) using a dip net and then placed into a holding tote containing flowing river water. One at a time, fish were then placed into a second tote, containing a mixture of clove oil (3 mL), food-grade ethanol (10 mL), and freshwater (~10 L). This mixture served as an anesthesia, employed to minimize stress during the handling and tagging procedure. Once fish appeared visibly calmer, their fork length (mm) and weight (g) were recorded, followed by the insertion of a pre-recorded PIT tag. Tags were inserted into the body cavity through a small incision made behind the pelvic fin with a surgical scalpel sanitized with rubbing alcohol. Fish were then placed in a lobster crate secured inside the submerged research trap, to allow recovery after tagging. The fishway trap screen was then removed, and river herring were released into the fishway trap once each fish exhibited normal swimming and schooling behavior.

Figure 1 The live-sampling station in the MGS fishway used to collect physical information of each fish. PIT tag being inserted into river herring (middle) and fish in recovery tote in flowing river water within the fishway (right).

Tracking

A network of 9 antennas were placed within five fishways along the river: MGS, Magurrewock Stream, Woodland dam, the Grand Falls dam powerhouse, and the Vanceboro dam. There were two antennas installed at MGS, one at Magurrewock Stream, three at Woodland, two at Grand Falls, and one at Vanceboro. The inclusion of a third antenna at the Woodland dam aimed to enhance detection capabilities and better track fish passing the true entry point of the fishway for a more precise analysis of fishway efficiency. All antennas were constructed using a pass-through design, utilizing 12G AWG stranded copper wire tuned to an inductance range between 41.8 and 78 µH. The wire was housed within PVC pipes, with an average of three loops to complete each circuit. Figure 2 illustrates what an antenna array would look like before being installed within a fishway.

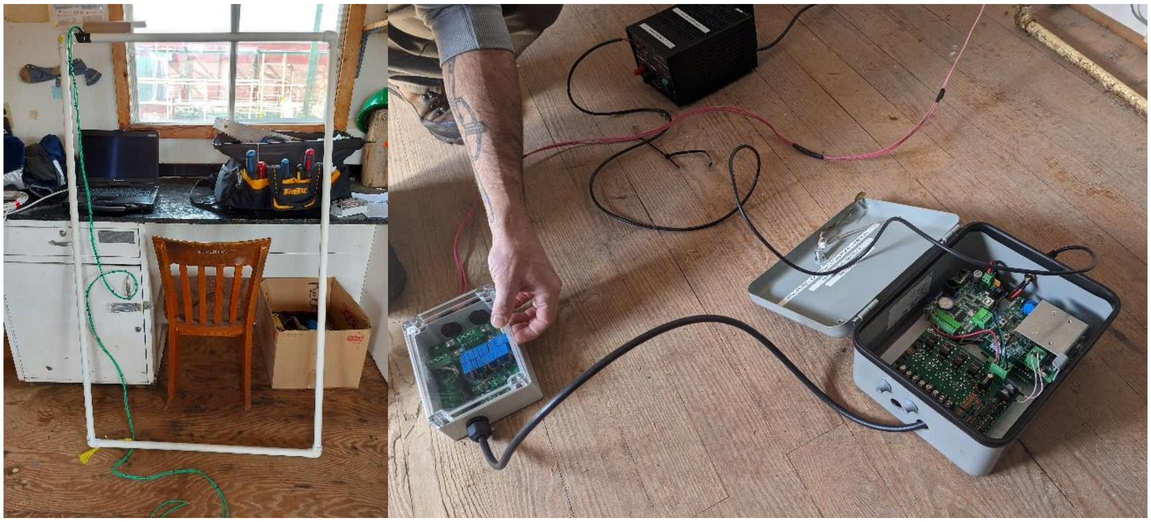

Figure 2 Example of an uninstalled PIT tagging reader and antenna system. From left to right: antenna encased in PVC pipe, autotuner, AC to DC power converter (background), reader. Marker tag is not included in the figure.

Marker tags were installed at each antenna array during the 2023 season to help ensure uninterrupted operation for each unit. Marker tags contain a built-in PIT tag that is programmed to send out pulses at a pre-determined frequency (i.e. every 30 minutes). By placing these pieces of equipment within each antenna's detection zone, breaks in the detection log can be tracked to help determine potential malfunctions in the reader, antenna, or power supply.

Table 1 Summary of PIT antennas and monitoring equipment in the St. Croix River 2023 with antenna installation and removal dates.

Location	Antenna	Inductance (µH)	Marker Tag	Reader Name	Power Source	Start Date	End Date
Milltown Generating Station (MGS)	Entrance (A1)	60.9	Yes	Milltown Entrance	Outlet	May 3	June 30
	Exit (A1)	53.7	Yes	Milltown Exit	Outlet	April 13	
Magurrewock	Exit (A2)	58.8	Yes	Magurrewock	Solar/ Marine Battery (2)	April 21	July 26
Woodland	Entrance (A1)	42	Yes	Woodland Entrance	Outlet	April 26	July 26
	Second (A2)	42.8	Yes		Outlet		
	Exit (A1)	42.6	Yes	Woodland Exit	Outlet	April 28	
Grand Falls	Entrance (A1)	43.4	Yes	Grand Falls Entrance	Outlet	April 20	July 24
	Exit (A1)	41.8	Yes	Grand Falls Exit	Outlet		
Vanceboro	Middle - Exit (A1)	73.9	Yes	Vanceboro	Outlet	May 11	July 24

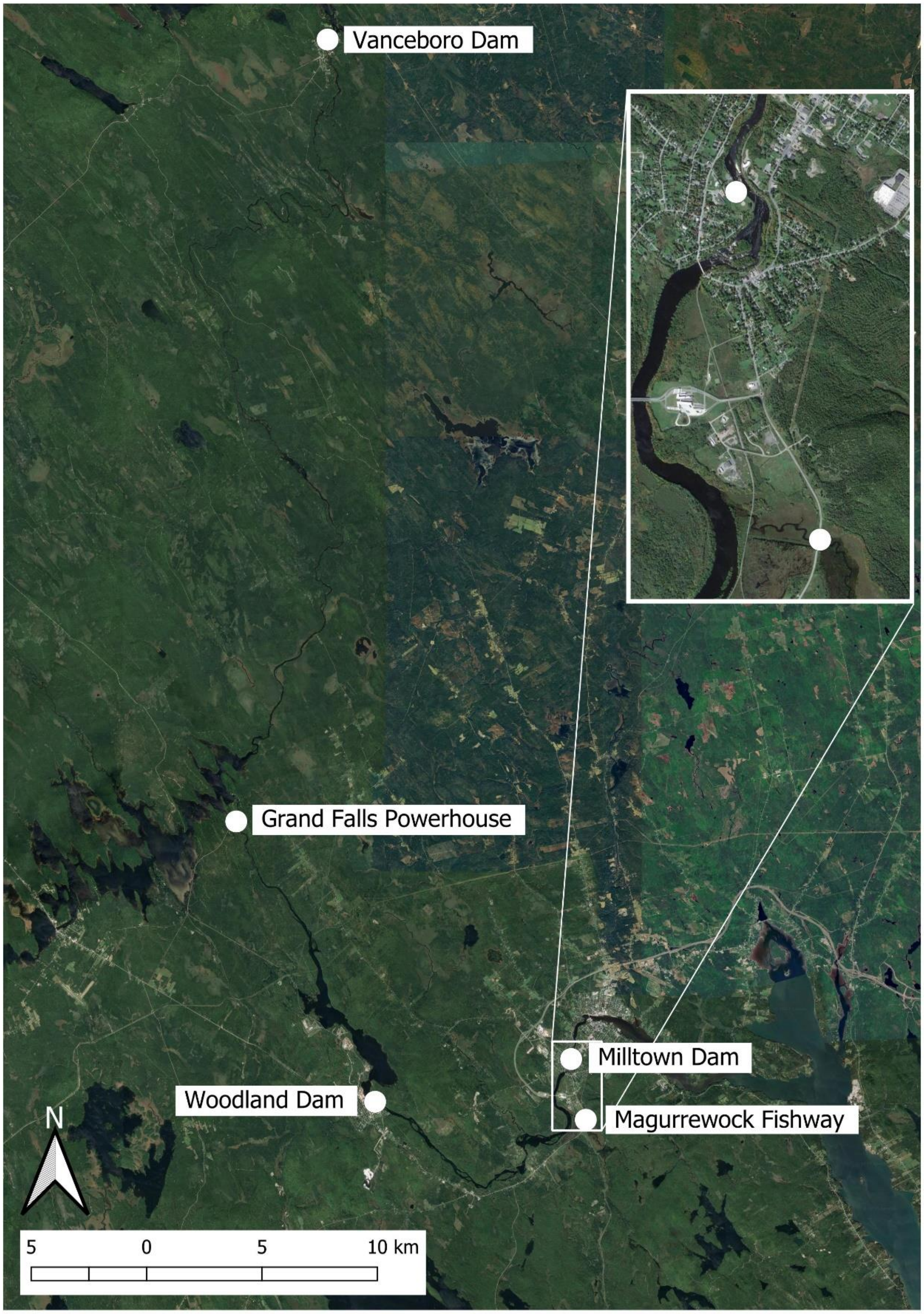

Figure 3 Overview map of PIT antenna placements at dams within the St. Croix watershed in 2023.

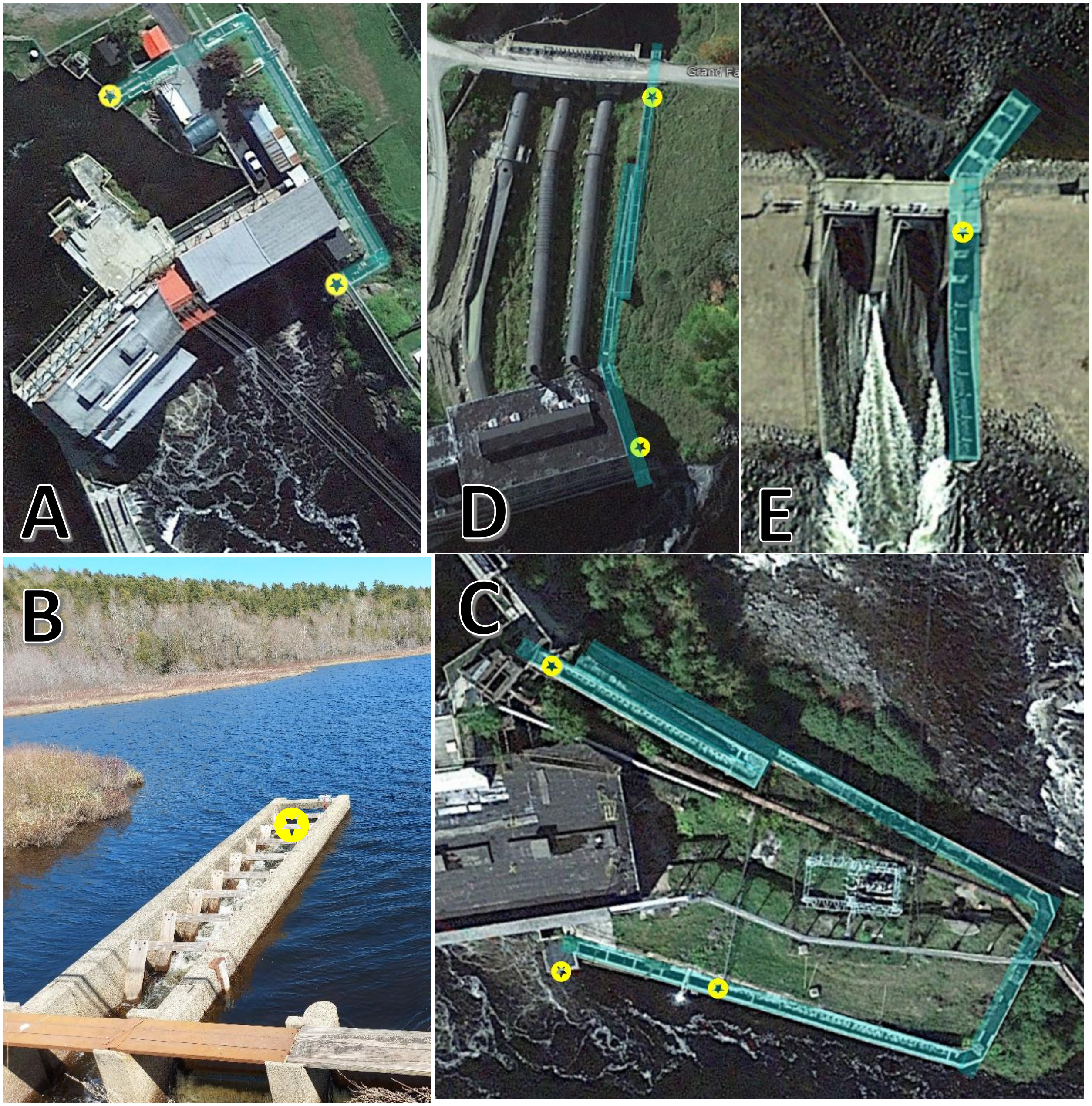

Figure 4 Antenna locations in fishways, stars indicate antenna and blue highlighting shows fishways at A) MGS, B) Magurrewock, C) Woodland Dam D) Grand Falls Powerhouse, E) Vanceboro Dam

At MGS, the first antenna was secured by NB Power personnel to the sluice gate positioned at the entrance of the fishway, while the second antenna was placed at the true exit of the structure. At the Magurrewock denil fishway, situated underneath the Route 1 highway just outside of Calais, Maine, within the Moosehorn National Wildlife Refuge, a single antenna was set up at the fishway exit. The Woodland dam denil fishway was installed with a total of three antennas: one at the true entrance of the fishway, a second positioned above the entrance on the 17th baffle to help distinguish between fish pooling at the fishway entrance from those actively ascending the fishway, and a third at the fishway's exit. The Grand Falls powerhouse denil fishway was equipped with two antennas: the first at the fishway entrance and the second at the exit. Lastly, an exit antenna was installed at the Vanceboro dam fishway, approximately four baffles before the actual exit.

Antenna arrays were powered at the MGS, Woodland, Grand Falls, and Vanceboro dams by outlet power. The Magurrewock fishway antenna array was powered by a 100-watt solar panel connected to two 12V marine deep-cycle batteries ran in parallel (Figure 5). To ensure the proper functioning of the equipment, marker tags were affixed to each antenna. Staff maintained a log of antenna performance during site visits, documenting routine maintenance conducted, adjustments made, and any instances of equipment malfunction.

Figure 5 The solar array set up at the Magurrewock denil fishway, situated under the Route 1 highway outside of Calais, Maine, within the Moosehorn National Wildlife Refuge.

Data Acquisition and Maintenance

Prior to the start of the 2023 spawning season, any historical data from previous years was erased from the readers to optimize storage availability. The readers were configured to capture tags in decimal format. Throughout the field season from April to July, the readers were visited once or twice a week. However, both readers at MGS were checked each day (excluding holidays and weekends) as staff members were present on-site to conduct the fish count. During these visits, all data from the most recent upload were transferred to a Toughbook laptop using the 'PuTTY' terminal software. The settings for the session logging involved selecting 'all session output' and a serial speed of 57600. Filenames were organized based on location, antenna name, and the download timestamp, which was automatically generated by the PuTTY software (e.g., “Milltown_entrance05242023153031.putty”). These data files were then uploaded to a Dropbox fileshare in a folder categorized by dam location, where it could be opened using Notepad for review. To ensure antenna functionality, all antennas were tuned using an Oregon RFID tuning indicator tool, and detection ability was tested using a spare PIT tag. Additionally, the date and time were verified and adjusted if there was any drift. If the reader was found to be offline during the visit due to disturbance or power supply issues, it was documented in a field book and then corrected, having batteries replaced if necessary and adjusted to prevent future outages. In cases where readers were potentially damaged, they were substituted with spare readers to minimize data loss.

Data Quality and Analysis

The SCIWC undertook the cleaning and analysis of all collected data, with technical assistance from PRGI. Fork length and weight collected from live samples during each PIT tagging procedure were reviewed for outliers. This task was typically carried out by the tagging staff after concluding the fieldwork. Prior to the end of each week, collected data underwent a secondary cleaning and analysis within the RStudio coding program. This process involved checking for typos, ensuring data recording was consistent, re-evaluating for potential outliers, and verifying the unique fish ID numbers. After completing tag-data cleaning, all downloaded detection data from the PIT readers were consolidated into a single flat-file. Antennas were arranged from the lowest downstream to the most upstream to help determine fish direction/timing, and extraneous reader data such as marker tags, test tags, and operational information were removed. Subsequently, analysis of fish tags from both the current year and previous years was facilitated utilizing R packages such as 'PITR,' 'tidyr,' 'dplyr,' and 'lubridate'. Manual confirmation of all detections and assumed crossings was conducted using commands entered within Excel, followed by the organization of the data into a series of informative graphics.

RESULTS

Tagging

In 2023 a total of 499 river herring were surgically implanted with PIT tags. No attempts were made to tag American Shad. Tagging was evenly distributed between females and males encompassing 234 females (46.9%), 234 males (46.9%), and 31 fish categorized as unknown or unidentified (6.2%). The average length for tagged female river herring was 253.3 mm, with an average weight of 231.8 g. Male fish were smaller, with an average fork length of 243.8 mm and an average weight of 208.4 g. Efforts were made to distribute tagging proportionally amongst the overall population, with a lower number of fish tagged during the beginning and end phases of the upstream migration, and more fish tagged during the peak of the migration (Table 2).

Table 2 River herring tagging schedule at MGS by week. Note the proportions of total fish counted by week were determined from the final 2023 river herring count of 841,357 fish.

Date	Number of Fish Tagged	Proportion of Total Fish Tagged	Proportion of Total Fish Counted at MGS
April 30 – May 2	0	0.0%	0%
May 3 – May 9	40	8.0%	8.8%
May 10 – May 16	51	10.2%	10.0%
May 17 – May 23	80	16.0%	15.3%
May 24 – May 30	150	30.1%	18.7%
May 31 – June 6	80	16.0%	21.5%
June 7 – June 13	40	8.0%	17.2%
June 14 – June 20	50	10.0%	4.5%
June 21 – June 27	8	1.6%	3.3%
June 28 – July 4	0	0.0%	0.5%

Antenna Functionality

Milltown Generating Station (MGS)

The two antennas at MGS were both equipped with marker tags and experienced no instances of power outages during the study period, as both units were connected to the generating station's power grid via outlet. Originally, a third preinstalled antenna was intended for use at MGS, positioned just beyond the research trap, however, due to technical challenges the multi-unit reader was unable to function using two antennas, and safety concerns prevented the removal of the trap exit antenna for potential repairs. It was decided to keep the true exit antenna as the sole antenna within the upper portion of the fishway.

Magurrewock

The Magurrewock antenna array was powered by solar in 2023 to help minimize gaps in functionality due to depleted batteries, a recurring issue in previous studies. With the addition of this new power supply, a marker tag was able to be installed and ran throughout the study. Subject to extended periods of little to no sunshine (especially in June), the antenna system was inoperative for a total of 369 hours within the window of regular fish migration (i.e. 6am to 10pm) from May 1st to July 26th, when the antenna array was removed (Figure 6).

Woodland

The marker tag at the true Woodland entrance antenna did not function during late April and throughout May due to being placed too far away from the antenna. Additional antenna interference issues caused potential missed detections at the Woodland true entrance antenna during the month of May. Several modifications were made to improve signal strength for each of the 3 antennas, including movement of equipment and replacement of wire and autotuners. By the beginning of June, all antennas were operating adequately despite minor interference from metallic structures present within the dam's fishway.

Grand Falls

The marker tag at the entrance of the Grand Falls fishway did not operate as intended throughout the season, despite the rest of the array system demonstrating the strongest performance among all the antennas. Both battery and tag replacements were common throughout the study period until the end of July when the entrance marker tag was left off permanently. Possible reasons for continued technical issues may have been from interference from nearby metal structures or other scientific equipment present at the fishway. Additional interference and brief power outages caused potentially missed detections at the exit antenna throughout the month of May.

Vanceboro

The Vanceboro antenna was operational for much of the field season, with a total of 10 days noted where the antenna array was not functioning (Figure 7). The antenna array was present within the fishway between May 11 and July 24. The 10 inoperative days were attributed to one 2-day power outage at the dam and one equipment flooding incident, on account of heavy rainfall.

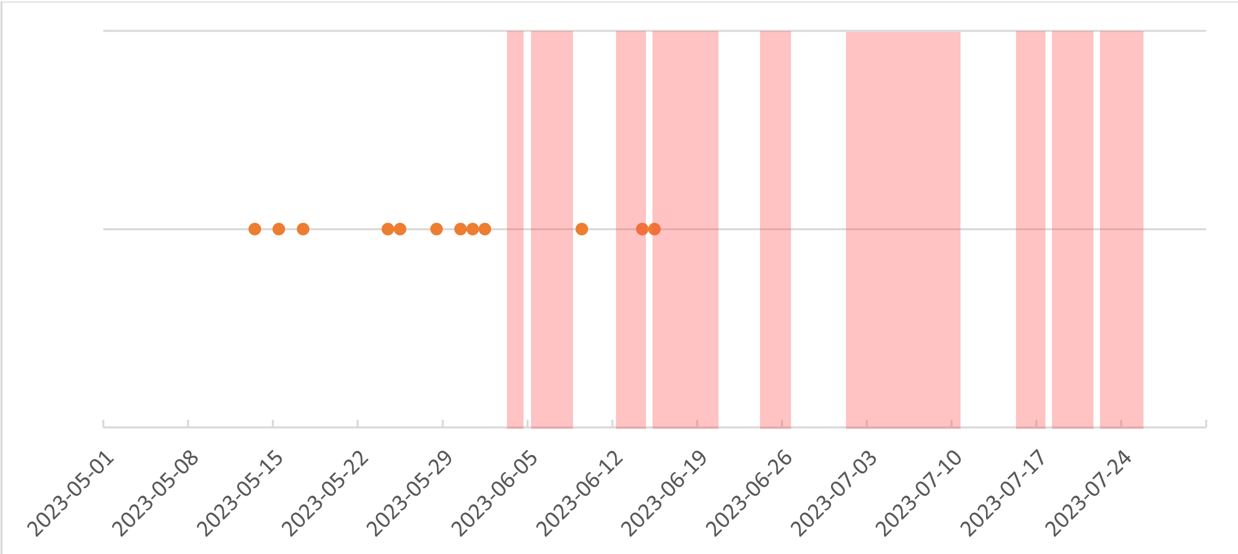

Figure 6 Timeline of fish detections (in orange) and power supply outages (in red) at the Magurrewock fishway denil.

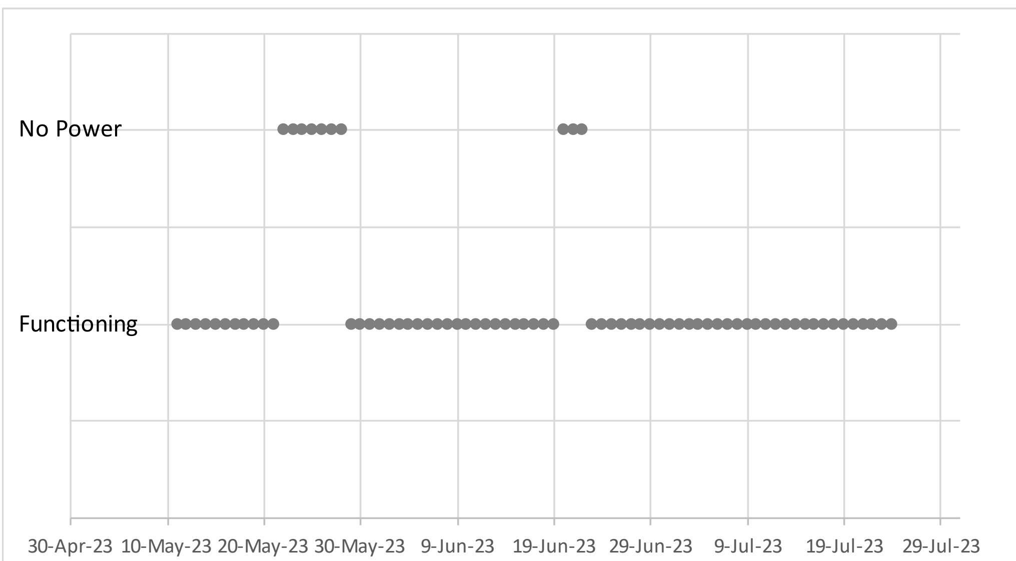

Figure 7 Vanceboro fishway antenna functionality.

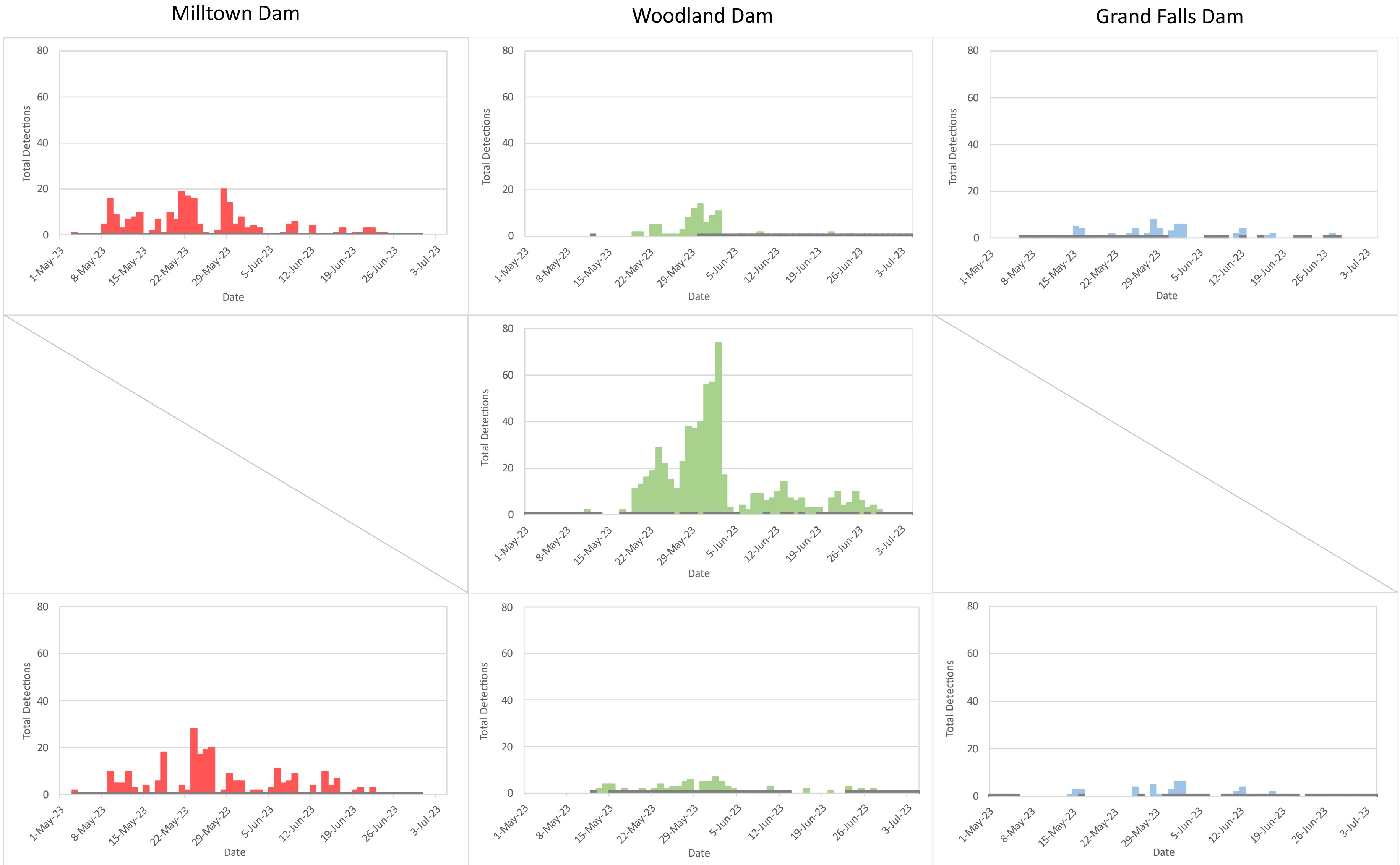

Figure 8 Number of fish detected (in color) per dam and antenna with marker tag functionality (in grey). Note: numbers on the left indicate antenna numbers ranging from most downstream (1) to most upstream (3).

Table 3 Number of operational days from installed marker tags compared to the 2023 fish detection window, from May 3 to June 30.

Antenna	MGS Entrance	MGS Exit	Magurrewock	Woodland Entrance 1	Woodland Entrance 2	Woodland Exit	Grand Falls Entrance	Grand Falls Exit	Vanceboro
Operational Days	59	59	48	33	43	39	37	34	41
Proportion of Study Period (May 3-June 30, 2023)	100.0%	100.0%	81.4%	55.9%	72.9%	66.1%	62.7%	57.6%	80.4%

Detections

A total of 568 individual fish were detected by at least one of the antennas positioned along the St. Croix River in 2023. From this total, 172 fish were identified as returns, having been tagged in earlier years (Table 3). One of these fish was identified as a blueback herring originally tagged at the Mactaquac dam on the St. John River by the University of New Brunswick in 2022. This fish was detected at the MGS entrance and was not detected at any upstream antennas. Of the 499 river herring tagged in 2023, 396 were successfully detected after tagging. 103 of the fish tagged in 2023 went undetected, representing 20.6% of the total study sample. Of the 396 fish detected post-tagging, 287 fish were detected at antennas upstream of the MGS fishway exit (72.3%).

Table 4 Number of individual fish detected in 2023 by the year the fish were tagged.

	2023	2022	2021
Number of Individual Fish Detected in 2023	396	129	43

There were also fish detected that were tagged in previous years which were classified as returning fish (Table 3). Of the 568 individual fish detected, many of these fish were detected crossing multiple antennas as each fish made their journey toward their chosen spawning habitat. In 2023 a total of 1020 unique detections were registered across all antennas during the migration period, from May 3 to June 30 (Figure 9).

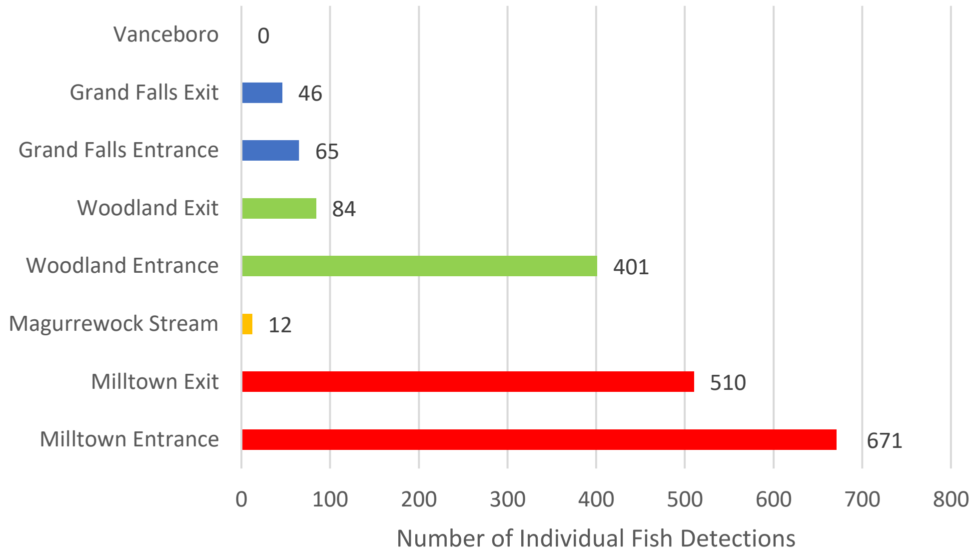

Figure 9 Number of individual fish detected per dam per antenna. Note: the 499 fish tagged at MGS were included in fish detected at the Milltown entrance.

In assessing the effectiveness of fishways, the exit efficiency for each dam equipped with both entrance and exit antennas was individually calculated. Additionally, the proportion of fish passing through each dam was determined based on the number of fish tagged and detected at MGS. Two key assumptions were made for analysis: 1) If a fish was detected at an upstream antenna, the fish would have also passed through and been detected at a downstream antenna (for mainstem dams only). 2) The 499 fish that were tagged inside the fishway at MGS were counted as "detected" at the MGS entrance antenna. Applying these assumptions, the analysis revealed that of the 671 fish detected at the MGS entrance, 76.01% were detected successfully exiting MGS (510), 1.79% (12) of these fish were detected entering Magurrewock stream, 12.75% (84) successfully exited above the Woodland dam, and 6.98% (46) of the tagged detected fish passed the exit of the Grand Falls fishway (Table 4).

Table 5 Exit efficiency of each fishway as well as cumulative efficiency of total tagged fish run across all dams. Note: the 12 fish that entered Magurrewock were not factored into calculations for Woodland and Grand Falls. **Only one antenna was present at Magurrewock.

Dam	Number of Fish Detected at Dam Entrance (Proportion of Fish that Exited Previous Downstream Dam)	Number of Fish Detected at Dam Exit (Proportion Detected Exiting that Were Detected Entering)	Proportion of Total Detected Fish Exiting (%)
MGS	**671** (100%)	**510** (76.01%) ((510 ÷ 671) x 100)	**76.01%** ((510 ÷ 671) x 100)
Magurrewock	**12** (2.35%) ((12 ÷ 510) x 100)	N/A**	**1.79%** ((12 ÷ 671) x 100)
Woodland	**401** (80.52%) ((401 ÷ (510-12*)) x 100)	**84** (20.95%) ((84 ÷ 401) x 100)	**12.75%** ((84 ÷ (671-12*)) x 100)
Grand Falls	**65** (77.38%) ((65 ÷ 84) x 100)	**46** (70.77%) ((46 ÷ 65) x 100)	**6.98%** ((46 ÷ (671-12*)) x 100)
Vanceboro	**0**	N/A	**0%**

Using the proportion of the tagged fish successfully ascending each dam, one can extrapolate the number of fish successfully passing each fishway using the total number of river herring counted at MGS. With a river herring population size of 841,357 having ascended the MGS fishway (SCIWC, 2023), one can estimate the number of fish successfully crossing upstream fishways and entering different sections of the watershed (Table 5). Note that for this study, fish detected at Magurrewock stream were assumed to have successfully ascended the fishway.

Table 6 Cumulative proportion of tagged fish exiting individual fishways from MGS to Grand Falls. Extrapolated number of river herring passing each fishway calculated from the 2023 MGS fish count total. Note: the 12 fish that entered Magurrewock were not factored into Woodland and Grand Falls efficiency and estimate calculations.

Barrier	Proportion of Tagged Fish Passing Barriers That Passed Through MGS (%)	Estimate of Total Number of Fish Passing Barrier
Exiting MGS	N/A	841,357
Entering Magurrewock	1.79%	15,060
Exiting Woodland	12.75%	107,273
Exiting Grand Falls	6.98%	58,726

Further analysis of the river herring migration examined the amount of time fish had appeared to spend navigating/ascending mainstem dam fishways. This was determined by subtracting the time and date of the first detection at the entrance antenna from the time and date of the last detection at the dam's exit antenna. This was only applied to fish detected at both the entrance and exit antennas within the MGS, Woodland, and Grand Falls fishways. On average, fish spent 1.71 hours at MGS, 23.77 hours at Woodland, and 1.23 hours at Grand Falls (Figure 10). Twelve (12) fish were also noted using the Woodland fishway for downstream passage. Downstream passage was inferred by observing fish that previously passed upstream, and then were detected again at the exit antenna, then a short time later at the entrance antenna. Downstream passage in the Woodland fishway was usually short, in the order of 1-2 hours.

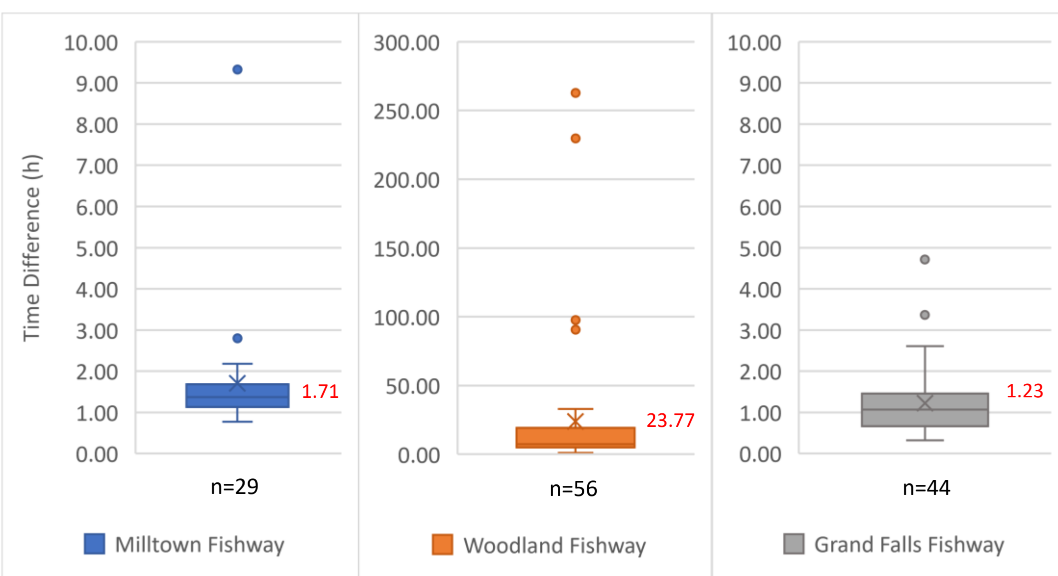

Figure 10 Time spent ascending fishways that had both entrance and exit antennas. Mean time in red.

In addition to time spent within fishways, time spent travelling between each dam was determined from the tagged river herring detected at several fishways along the river (Figure 11). From the MGS exit to the fishway exit at the Magurrewock fishway denil, river herring spent an average of 2.12 days traversing this 4.25 km stretch of the St. Croix (n=5). Further upstream, the journey from the MGS exit to the entrance of the Woodland Dam had taken fish on average 8.77 days to travel the 15.5 km section (n=137). From the Woodland fishway exit to the Grand Falls fishway entrance, it took an average of 2.18 days to traverse the 15.09 km section (n=62). Of the individual fish both detected at the MGS exit and Grand Falls entrance, the average travel time was 10.40 days over a distance spanning 30.57 km (n=22). Please note that the time between the MGS exit and the Grand Falls entrance would include time spent ascending the Woodland Dam fishway.

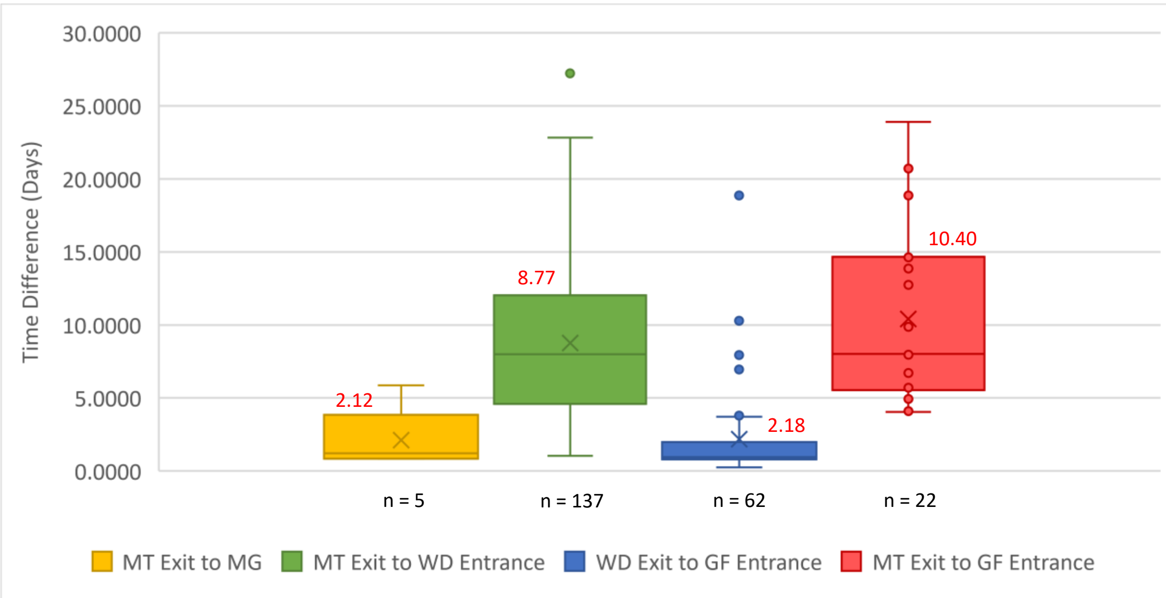

Figure 11 Time spent by river herring swimming between dam fishways. Mean time in red. Please note that the time spent between the Milltown (MT) exit and Grand Falls (GF) entrance includes time ascending the Woodland (WD) fishway.

DISCUSSION

In 2023 a total of 499 fish were successfully tagged, spanning from early May to late June. Most of the tagging occurred during the peak of the upstream migration, from mid-May to early June. Only five mortalities occurred during tagging, and in these cases, the PIT tag was removed, and the fish was used in lethal sampling efforts authorized under DFO fishing permit #343928. A total of 103 fish that were tagged at MGS went undetected post-tagging. In telemetry studies of fish, tagging may induce physiological stress in response to handling, and physical trauma, which can affect behaviour. It is possible that some of the 103 fish that were not detected post-tagging did not continue their upstream migration due to tagging, handling, and stress. Other significant factors in the detection of post-tagged fish could be predation, stress caused by temperature fluctuations, and functionality issues with antenna arrays.

Marker tags were installed at each antenna in 2023 and were set to be detected every 30 minutes. This had proven useful in understanding antenna functionality, though some marker tags experienced malfunctions during the study period. Despite these challenges, results indicated that marker tags at each antenna were operational for much of the time within the window between the first and last tag detection (i.e. May 3 to June 30) (Table 6). In addition to marker tags, regular testing of antennas using a spare PIT tag during weekly data downloads helped ensure antenna functionality. To enhance confidence in antenna performance in future tracking studies, considerations could include marker tag checks during each antenna visit and installing them in the most easily accessible locations for regular battery replacement.

During site visits at the Route 1 denil fishway at Magurrewock Stream, schools of river herring were observed from mid May to early June. River herring were also observed at the Magurrewock Upper dike Alaskan steep-pass fishway just upstream of Route 1 (Figure 12), and the Howard Mills Alaskan steep-pass during the migration. Fish were observed successfully ascending these structures within the Moosehorn National Wildlife Refuge, although high water levels at times simply allowed fish to bypass the steep-pass structures. High water levels in the Magurrewock impoundments and stream portions during the migration period likely afforded greater access to spawning habitat within the Magurrewock system. Anecdotally, the number of river herring utilizing the Magurrewock system seems to be increasing (Indian Township Wildlife Dept., pers. comm.). It is likely that more fish will be migrating up this key tributary for spawning following the removal of the Milltown dam.

Detection results in 2023 closely mirrored 2022, with similar numbers of returning fish that were tagged in previous years (179 returning fish detected in 2022, 172 detected in 2023). Like results from the 2022 PIT tracking study, the Woodland Dam fishway remained the biggest impediment to the passage of river herring, with 80.52% of the fish that successfully passed through MGS detected at the Woodland entrance and only 20.95% of those fish detected exiting the Woodland dam. This fishway exhibited the poorest exit efficiency among the 5 dams, passing 12.75% of the total tagged run. Potential challenges for fish attempting to ascend the fishway include poor attraction flow to the entrance of the fishway, false attraction to the spillway area of the dam (observed during the study period), or unfavourable flow within the structure. The average time spent by tagged fish within the Woodland fishway was influenced by outliers, with some fish spending up to 263 hours ascending the structure. High fish traffic events were observed numerous times during the peak of the upstream migration at Woodland. These events can affect the antenna's detection ability as tag readers are only able to detect one tag at a time. Other possible reasons for this decline in detections, outside of antenna functionality, include an increase in predation at this site by avian predators. In addition to detecting tagged fish using the fishway for downstream passage, observations of fish ascending and descending the fishway were observed during late June.

At the Grand Falls powerhouse, adult river herring were first observed on June 15th attempting to migrate downstream. This also simultaneously occurs with adults still migrating upstream. The operation of the log sluice at Grand Falls appears to be crucial in facilitating the downstream passage of out-migrating adults in the power canal. Entrainment of adult river herring at the trash rack was observed during periods when the log sluice was not operating. The log sluice is only operational during times when a dam tender is present at the powerhouse due to safety and operational concerns at the site.

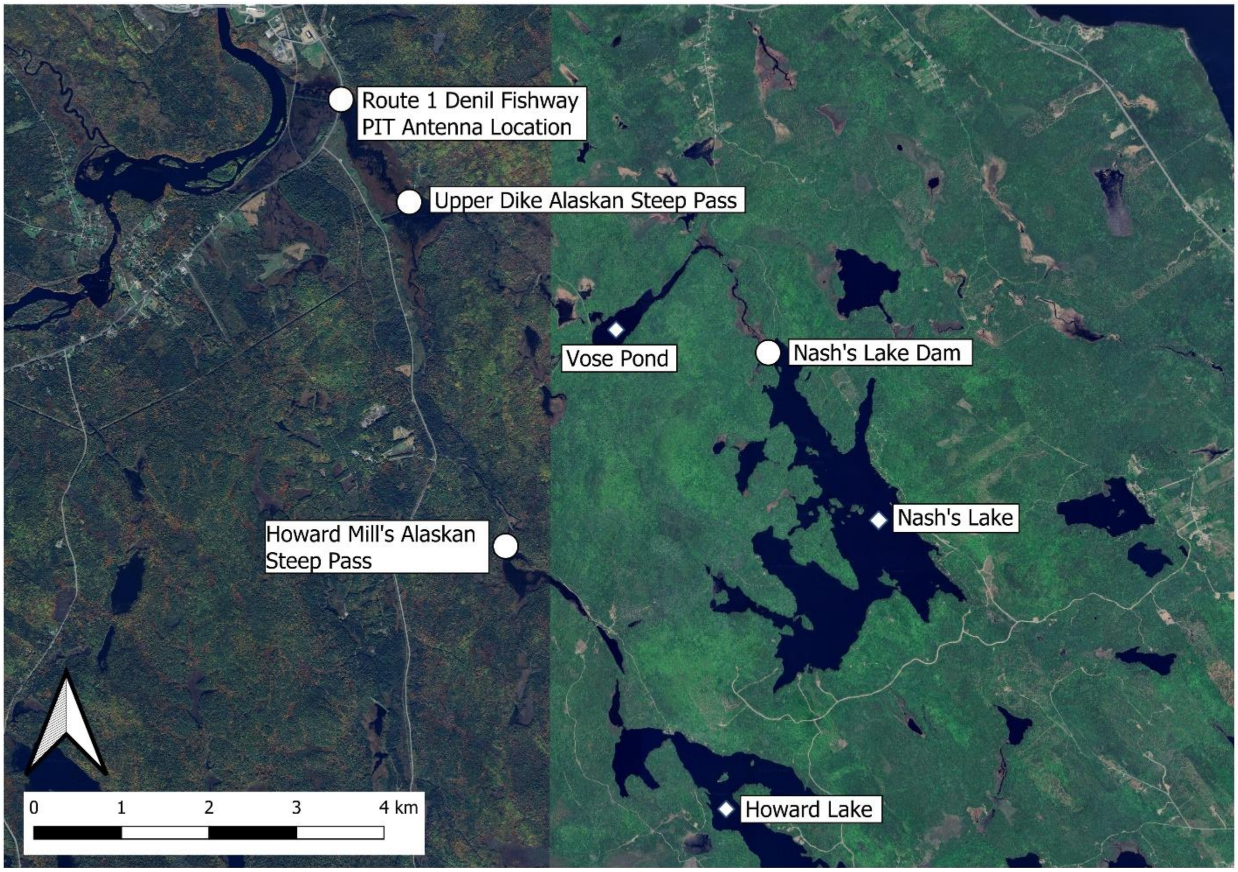

Figure 12 Magurrewock watershed points of interest. Note: Nash's Lake dam currently has no fish passage. Note: Howard Lake and Nash's Lake are outside of the boundaries of the Moosehorn National Wildlife Refuge.

Typically, the log sluice was operated during the morning, until approximately 13:00 hours EST. Young-of-year (YOY) river herring were observed congregating at the power canal, and it was observed that downstream passage for YOY was primarily through the attraction flow pipe and the log sluice (Figure 13). Both smallmouth and largemouth bass were observed feeding heavily on YOY at the attraction pipe outfall during late June and early July. During site visits from June 23 – July 24, adult river herring were observed feeding on YOY at the power canal. This behaviour was noted as active feeding, and river herring were observed chasing and feeding on schools of YOY. For much of the study period, turbines 1 and 3 were noted as being operational.

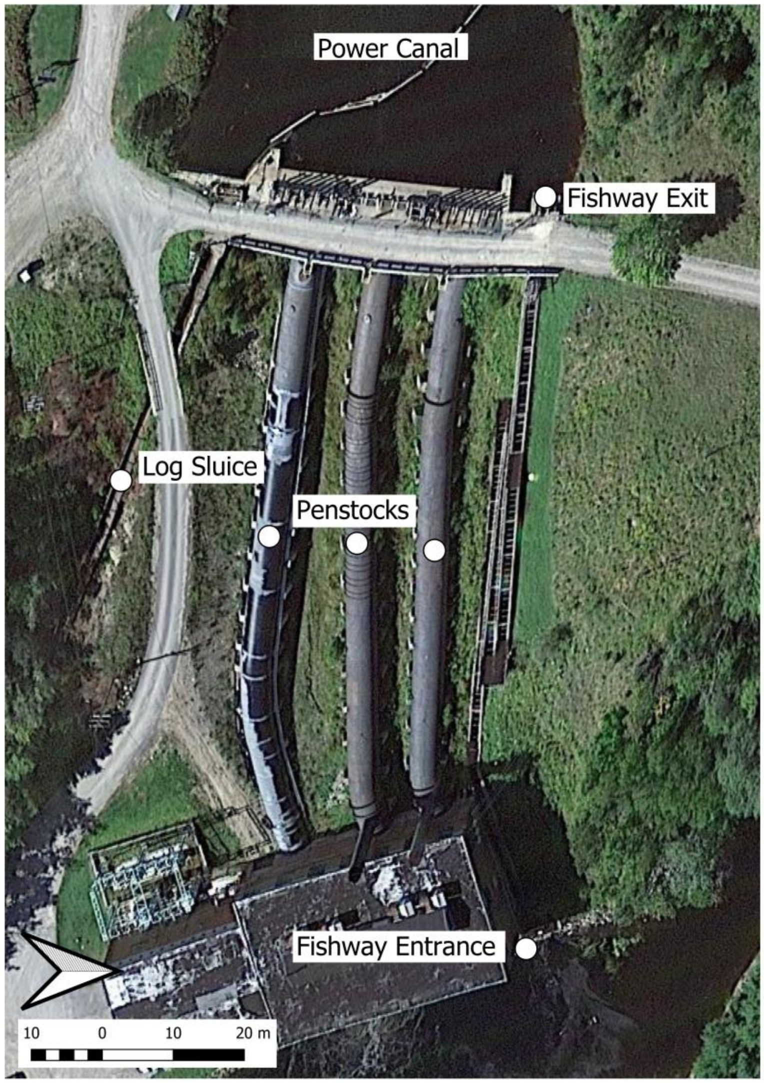

Figure 13 Aerial view of the Grand Falls Powerhouse and associated structures.

No tagged river herring were detected at the Vanceboro dam during 2022 and 2023. It is currently unknown if river herring are migrating up the East Branch St. Croix upstream of the Grand Falls dam. Anecdotally, river herring were observed migrating upstream in the West Branch of the St. Croix as far as Grand Lake Stream and possibly beyond in 2023 (SED, personal comm.). It seems logical that a portion of the fish that successfully ascend the Grand Falls fishway would continue to migrate upstream towards Vanceboro and Spednic Lake, however, we have uncovered no evidence of this during 2022 or 2023. It is possible that fish are utilizing this upstream pathway, and that numbers are not high enough for fish to be noticed. A future telemetry study could focus on pathway choice for fish that have successfully migrated above the Grand Falls fishway.

To access critical spawning grounds, the vast majority of river herring must ascend three large mainstem dams (MGS, Woodland, Grand Falls) in short order during the annual migration period. Results from successive years of tagging show that tagged fish that are successful in ascending above the Grand Falls powerhouse are significantly larger than the average size of fish from the overall tagged fish population (Tables 7 and 8). Larger river herring would have, in theory, increased fat stores and be stronger swimmers than smaller fish. The possibility of population-level consequences in St. Croix river herring may arise from the theory that predominantly larger, older fish are the ones successfully reaching spawning habitat. Future studies and monitoring should investigate what effect the removal of MGS will have on the size of river herring at the population level, as one less barrier to pass could mean that smaller fish may have more energy to ascend subsequent barriers.

Table 7 Average length and weight of tagged river herring in 2023, 2022, and 2021. Note: SD=standard deviation.

Year Fish Were Tagged	Fork Length (mm)	FL SD (mm)	Weight (g)	Weight SD (g)
2023 (n=499)	249.8	19.3	222.6	41.1
2022 (n=525)	253.8	17.3	223.9	47.0
2021 (n=502)	252.4	18.7	222.1	45.3

Table 8 Average length and weight of tagged river herring that successfully ascended above the Grand Falls powerhouse by year the fish were tagged. Note: fish that were interpreted as returning fish that ascended above Grand Falls were not included in this table as their length and weight would be different than the year they were tagged. Note: SD=standard deviation.

Year Fish Were Tagged	Fork Length (mm)	FL SD (mm)	Weight (g)	Weight SD (g)
2023 (n=28)	264.6	11.8	253.0	34.1
2022 (n=40)	257.6	13.2	237.4	42.3
2021 (n=53)	265.7	12.0	255.8	37.0

Estimates of the number of river herring passing barriers in this study should be interpreted with caution due to a myriad of factors including antenna functionality, low sample sizes, and the effects of tagging. Estimates of population sizes in this study serve to provide data on individual fishways, pathway choice, and the cumulative effects of barriers on this migratory species.

Due to the large amounts of precipitation during the 2023 study period (especially in June), water levels in the mainstem St. Croix and key tributaries remained high. During years when there are average or below average amounts of precipitation in May and June, the water level of the mainstem St. Croix can be low. The cause of this can be attributed to FERC license conditions at the Vanceboro and West Grand Lake storage projects which limits impoundment fluctuations during the spring for waterfowl nesting purposes. This effectively limits the amount of water discharged at these storage dams during the spring if there is a lack of natural precipitation. During 2023, water flows measured at the Baring, Maine gauge operated by the US Geological Survey (USGS) were noted as low from mid-May to the beginning of June (Figure 14). High water levels during June likely afforded migrating fish better access to spawning habitats, as well as kept water temperatures lower. This contrasts with 2022 (Figure 15), in which water levels slowly decreased following the spring freshet as spring turned to summer.

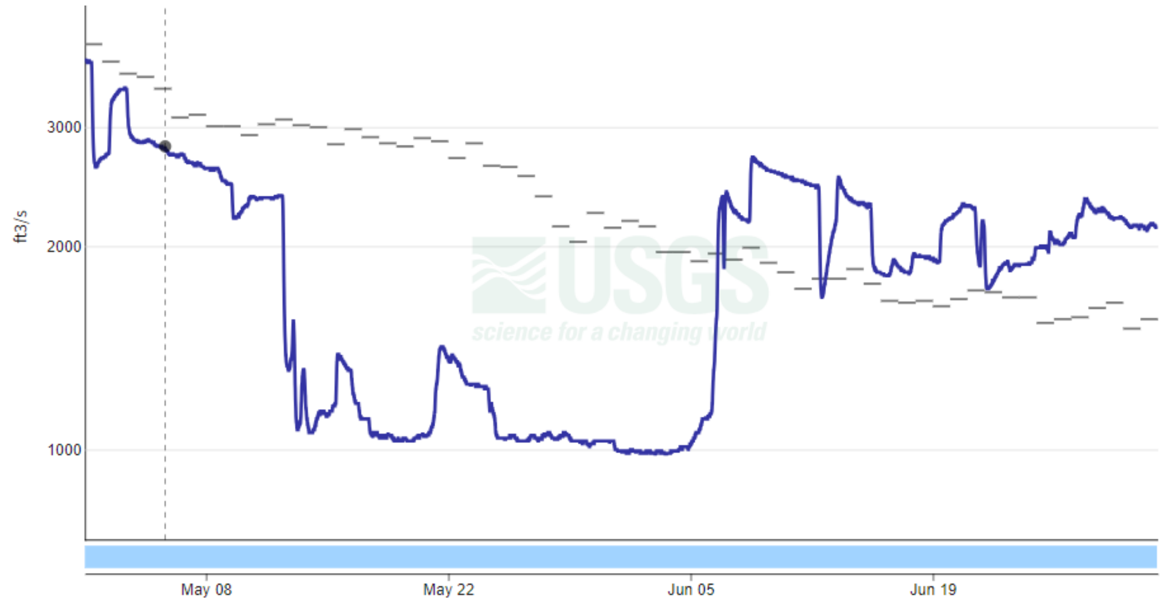

Figure 14 Water flow measured at the USGS Baring, Maine gauge on the mainstem of the St. Croix River downstream of the Woodland dam from May-July of 2023. Note: gray bars represent the median water flow for this station from 1960-2023.

Figure 15 Water flow measured at the USGS Baring, Maine gauge on the mainstem of the St. Croix River downstream of the Woodland dam from May-July of 2022. Note: gray bars represent the median water flow for this station from 1960-2022.

With the removal of MGS, river herring and other migratory diadromous fish will have unimpeded access to habitat above Salmon Falls for the first time in well over a hundred years. With approximately 98% of spawning habitat in the St. Croix watershed for river herring existing above the Grand Falls dam (Billard and Hoar, 2021), monitoring of both the Woodland and Grand Falls dams will be key in documenting passage of migratory species and the broader restoration of these fish in the coming years with planned passage improvements at both the Woodland and Grand Falls dams.

Lessons Learned

Insights gained this year that are relevant to the future of fish tracking in the St. Croix highlight the importance of strategically placed marker tags for accessibility. It is advisable to perform regular checks on the functionality of these tags to enhance confidence in determining antenna performance. Despite dealing with challenging weather conditions this season, PIT tracking arrays powered by solar could prove useful in locations where outlet power is not available. To further improve upon the design used in 2023, a second solar panel should be installed to increase the generating power of the system while also programming the reader to turn off during the night to conserve battery life.

Acknowledgements

We would like to thank the International Joint Commission for providing continued financial and logistical support for this project in 2022 and 2023.

Many thanks to:

John Sewell and Justin Socobasin – Passamaquoddy Tribe at Indian Township: Wildlife Department

Alexa Meyer and Bex Goreham – Passamaquoddy Recognition Group Inc.

Chris Johnson and Ralph Dana – Sipayik Environmental Department

John Magera, Ray Brown, Mike Krug, Maurry Mills, and Rebecca Cusick – Moosehorn National Wildlife Refuge

New Brunswick Power Corporation and Woodland Pulp LLC for the use of their facilities and their patience, time, and expertise.

Finally, we are grateful for the many individuals, agencies and departments, and stakeholders that donated their time, knowledge, guidance, and efforts in support of this project. Thank you.

REFERENCES

Billard, M., and Hoar, A.R. 2021. Alewife Spawning Habitat in the St. Croix River Watershed. 7pp. Fisheries and Oceans Canada, unpublished data.

Hare, J.A., Borggaard, D.L., Alexander, M.A., Bailey, M.M., Bowden, A.A., Damon-Randall, K., Didden, J.T., Hasselman, D.J., Kerns, T., McCrary, R., McDermott, S., Nye, J.A., Pierce, J., Schultz, E.T., Scott, J.D., Starks, C., Sullivan, K., Tooley, M.B. 2021. A Review of River Herring Science in Support of Species Conservation and Ecosystem Restoration. Marine and Coastal Fisheries 13: 627-664.

St. Croix International Waterway Commission. 2023. 2023 Anadromous Fish Counts at Milltown Dam. 7pp. Unpublished data.