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COMMUNITY-BASED MONITORING IN THE SAINT JOHN HARBOUR

REPORT FOR FISHERIES AND OCEANS CANADA'S COASTAL ENVIRONMENTAL BASELINE MONITORING PROGRAM 2018-2021

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Community-based monitoring in the Saint John Harbour

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Abstract

The goal of this project was to create a field program in the Saint John Harbour to collect aquatic environmental data on water quality, fish communities, and sediment PAHs in line with Fisheries and Oceans' Coastal Environmental Baseline Monitoring Program. The 2018 sampling season served as a pilot year for building the Harbour Baseline Monitoring Program, and there have been three full sampling seasons since. Water quality was analyzed at 22 sites, and of these sites, 13 were also sampled for sediment contaminants and 8 sites were surveyed for nekton communities via beach seine and fyke net. There was generally good water quality at most Harbour sites, except for certain sites, especially those in Marsh Creek and Little River. Marsh Creek and Little River are two streams known to have historic contamination from industrial and municipal effluents. *E. coli* concentrations exceeded the recommended guidelines at 14 sites, indicating a chronic problem with fecal contamination. Sediment PAHs were also high at 6 sites, particularly Marsh Creek; these sites are subject to a number of industrial contamination sources. We collected a total of 35,213 fish and invertebrates, representing 34 species, in beach seines and fyke nets. Spar Cove had the highest abundances but lowest richness and diversity, and species diversity was highest at Inner Harbour, Little River, Marsh Creek and Tin Can Beach. Lengths and counts of the most common species (Atlantic silverside, sand shrimp, Atlantic tomcod) varied temporally and spatially, potentially due to changes in environmental conditions.

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1. Introduction

The Saint John Harbour is located at the mouth of the Wolastoq (Saint John River) in New Brunswick, where it receives a mean annual discharge of 1,110 m^3/s of fresh water (Cunjak and Newbury 2004), including discharge from other watersheds. The Saint John Harbour is a dynamic system with an 8 m tidal influence in the Bay of Fundy (Trites and Garrett 1983); this system has a number of human influences, freshwater inputs, and other changing natural conditions. The Harbour contains a port with frequent shipping and dredging activities (Courtenay et al. 2002), as well as industrial (i.e., pulp and paper effluent, ballast water, and oil refinery effluent) and municipal discharges entering the aquatic ecosystem. The Coastal Environmental Baseline Program, a Canadian federal government environmental initiative, funded the development of an environmental monitoring program in 2016 for busy shipping ports in Canada to evaluate environmental indicators and baseline conditions. The Saint John Harbour was selected for this federal monitoring program because of its highly industrialized port. Identifying current baseline conditions in the Saint John Harbour will allow observations of significant changes in environmental indicators in future years or as new industrial or municipal developments occur.

Fish community monitoring has been used to detect anthropogenic changes in previous studies in watersheds around the Harbour (and for pre-design analysis for sentinel species monitoring programs; Arens et al. 2007; Casselman 2007; Vallieres et al. 2007; Methven 2003, unpublished data; Power 2012-2013, unpublished data). Mummichog (*Fundulus heteroclitus*), Atlantic silverside (*Menidia menidia*), and rock gunnel (*Pholis gunnellus*) have been investigated as sentinel species using previous fish community data collected in the Saint John Harbour and surrounding watersheds (Vallis et al. 2007; McMullin et al. 2010; Doyle et al. 2011). ACAP Saint John has historic fish community and water quality data dating back to the early 1990s for monitoring purposes in the Greater Saint John area, and has used these data to aid cleanup initiatives such as Harbour Cleanup (the cessation of raw sewage entering the Harbour in 2014).

Municipal and industrial discharges into aquatic environments can carry contaminants that accumulate in nearshore and offshore substrates (Doyle et al. 2011). Among these contaminants are polycyclic aromatic hydrocarbons (PAHs). PAHs are a group of organic contaminants that are released into the environment from the incomplete combustion of wood, coal, and fossils fuels. Sources of PAHs include car exhaust, industrial emissions, marine traffic, and residential emissions, and they are also used in products like pesticides, asphalt, and creosote (a preservative used on wood products). These compounds are typically released in complex mixtures and can be easily transported from land to water through rain, urban runoff, and snowmelt (Stogiannidis and Laane 2015). Most PAHs bioaccumulate and are acutely toxic to animals, and medium to larger sized PAHs are also carcinogenic (Manzetti 2013). PAH sampling in the Saint John Harbour over the last 2 decades has identified considerable PAH contamination within the sediments (Zitko 1999; Van Geest at al. 2015). Within the Harbour area, Marsh Creek is also known to contain extreme PAH contamination as a result of creosote applications at a former lumber yard on the banks.

2. Objectives and Significance

The goal of this project was to develop a field program in the Saint John Harbour focused on collecting baseline environmental data on water quality, sediment PAHs, and biotic communities. To be concurrent with Eastern Charlotte Waterways (an environmental not-for-profit organization overseeing the Charlotte County community), who have also collected baseline biological data in the region, sampling protocols were adapted from a Department of Fisheries and Oceans Canadian Technical Report (Ipsen 2016). ACAP Saint John's Harbour monitoring program serves to fill in data gaps in priority areas around the Harbour in line with Fisheries and Oceans' Coastal Environmental Baseline Monitoring Program.

Water quality monitoring is a key method for evaluating short- and long-term changes in aquatic ecosystem health. Monitoring fish communities can indicate a response to their habitat, i.e., a loss in species richness may indicate a negative change in the environment. Since PAHs are highly tied to oil and gas industries, vehicles, residential home heating, etc., they are an important parameter to examine in an industrialized area such as Saint John. The sites selected for this program are primarily concentrated around the most industrialized parts of the city's coastline, with some sites outside of the Harbour selected for comparative purposes. A continual baseline monitoring program in support of cumulative effects assessment (Duinker and Greig 2006) will be a crucial next step in determining the health of the Saint John Harbour.

3. Materials and Methods

3.1 Water Quality Sampling

Water sampling was generally completed within a two-hour window before or after low tide in the Saint John Harbour. There were 22 water quality sites (Table 1, Figure 1) sampled as part of this program. Water quality samples and measurements were collected bi-weekly or monthly between May and October each year, starting September 2018 and ending in October/November 2021.

Table 1. Sites used in the Saint John Harbour Baseline Monitoring Program with site codes and coordinates. Sediment sampling sites (for PAH analysis) and fishing sites (for biotic community analysis) are also identified.

Site	Site Code	Latitude	Longitude	Sediment Site	Fishing Site
Black Beach	BB	45.154591	-66.229004	X	
Saints Rest Beach	SRB	45.222523	-66.126761	X	
Bayshore	BS	45.244895	-66.075821	X	
Digby Ferry Terminal	DFT	45.253016	-66.062025	X	X
Mill Creek	Mill	45.279310	-66.155487		
Kennebecasis Drive	KD	45.305689	-66.095746		
Spar Cove	SC	45.276147	-66.090295	X	X
Inner Harbour	IH	45.272068	-66.073478	X	X
Tin Can Beach	TCB	45.262244	-66.054578	X	X
Courtenay Bay	CB	45.276202	-66.047032	X	X
Marsh Creek 2	MC2	45.281834	-66.049478		X

Marsh Creek Downstream	MCDS	45.282676	-66.049784	X	
Marsh Creek 3	MC3	45.284826	-66.052373		
Marsh Creek 4	MC4	45.289029	-66.047363		
Marsh Creek 5	MC5	45.291050	-66.043541		
Marsh Creek 11	MC11	45.309737	-66.033974		
Marsh Creek Upstream	MCUS	45.321672	-66.015109		
Little River	LR	45.272416	-66.022299	X	X
Hazen Creek 2/Expansion	HC2	45.275821	-65.999035		
Hazen Creek Nearshore	HCNS	45.258105	-66.020075	X	X
Hazen Creek Mouth	HCM	45.260928	-66.015080	X	
Mispec Beach	MB	45.223043	-65.954639	X	

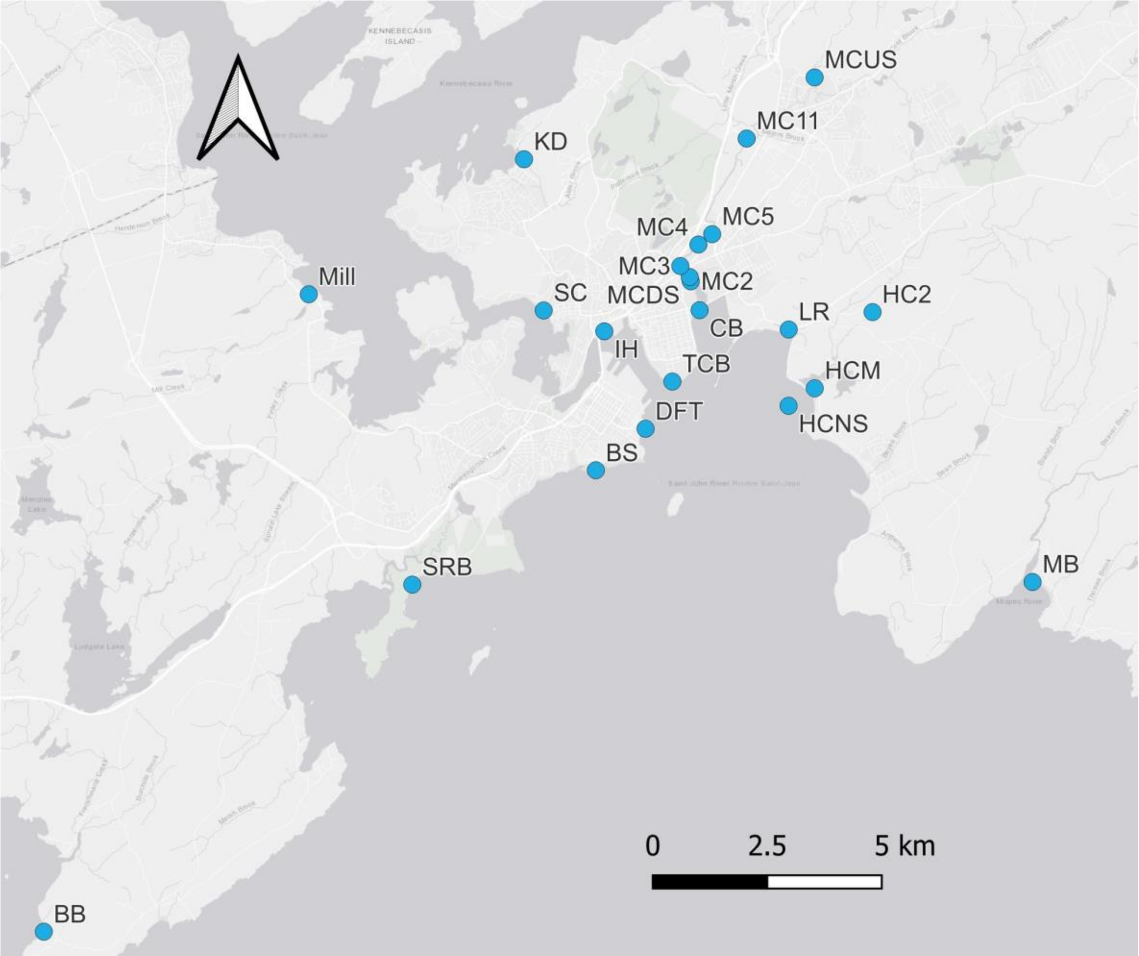

Figure 1. Map of sites in and around the Saint John Harbour. Site names and geographic coordinates are provided in Table 1.

A calibrated YSI multimeter was used to analyze *in-situ* water temperature (±0.1°C), dissolved oxygen (DO; ±0.01 mg/L and %), salinity (±0.01 ppt), conductivity (±1 μS/cm) and pH (±0.01). A turbidity meter was used to measure turbidity in the water (±0.01 NTU) (n = 1/site per date; two sampling events in 2018, 10 in 2019, 6 in 2020, 11 in 2021; Figure 2a). All reasonable efforts were made to remove measurements that were ecologically impossible or could not be validated. Due to the large amount of data, potential errors with equipment, the number of people that had a part in data collection and input, and the large amount of natural variability in conditions at many sites, some isolated datapoints within this dataset may be erroneous. All results are presented as a mean ± standard deviation (SD).

Starting in 2019, collected water samples were analyzed (Figure 2b) using a DR900 multiparameter colorimeter for total ammonia (±0.01 mg/L; blanks = 0.012 ± 0.026 mg/L, n = 24; duplicates within 30 ± 43 %, n = 32) and orthophosphate (±0.01 mg/L; blanks = 0.02 ± 0.015 mg/L, n = 24; duplicates within 33 ± 35 %, n = 33). In 2020 and 2021, orthophosphate (PO_4^{3-}) was further analyzed for phosphorous (P) in each sample (±0.01 mg/L; blanks = 0.001 ± 0.004 mg/L, n = 14; duplicates within 29 ± 39 %, n = 28). When access to the NBCC chemical technology lab was available from June – August 2019, total suspended solids and fecal coliform content (±1 cfu) were also analyzed.

Ammonia concentrations measured in 2021 were considerably higher than those measured in previous years. Blank samples with distilled water, which historically had concentrations around 0 mg/L, had concentrations around 0.07 mg/L. As a result, sample ammonia concentrations in 2021 were standardized to a new baseline concentration. However, ammonia concentrations in blank samples may have been even higher than 0.07 mg/L at some points in 2021, resulting in reported ammonia levels that are still elevated compared to previous years. Due to this uncertainty with the 2021 ammonia data, we also present ammonia results for each individual year in this report to better understand patterns in ammonia levels.

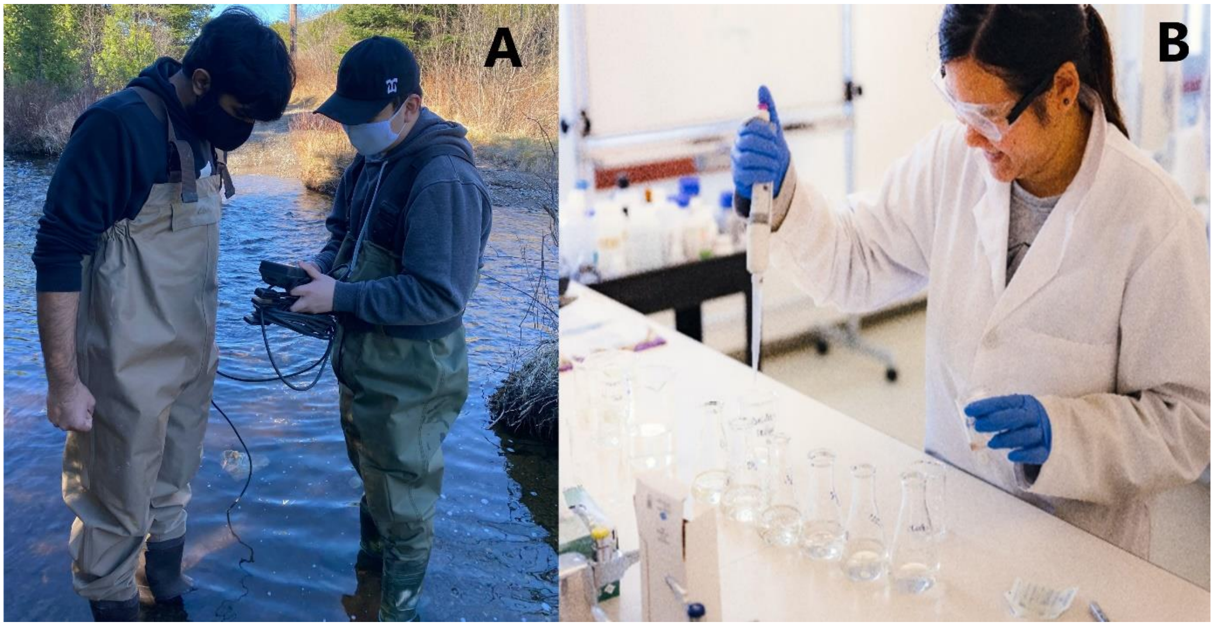

Figure 2. Water quality sampling and analysis methods. (**A**) Staff collecting data *in-situ* using a YSI Pro Meter Plus; (**B**) NBCC Chemical Technology student analyzing samples for ammonia using an alternate method.

Laboratory analysis of fecal coliforms was conducted on water samples in 2019. Starting in 2020, fecal coliform analysis was replaced with analysis of *Escherichia coli*, a particular species of fecal bacteria. Concentrations of total coliforms and *E. coli* were estimated using the IDEXX Colilert incubation system (±0.1 MPN/100 mL). The Colilert-18 reagent was added to 100 mL of sample and incubated in standardized trays at 35°C for 18 hours. The trays were removed from the incubator after eighteen hours. The number of yellow and fluorescing trays corresponded to the total coliform and *E. coli* concentrations, respectively, measured as the most probable number/100 mL (MPN/100 mL). If a site exceeded 2 ppt salinity, the sample was analyzed in a 1:10 dilution so that the salinity would not interfere with bacterial growth, and results were multiplied by ten to achieve MPN/100 mL. Total coliform counts are unreliable outside of freshwater sites; for this reason, total coliforms are not presented in this report, though they were observed. All *E. coli* counts at or above the detection limit (2419.6 MPN/100 mL) were assigned the detection limit as a value. This method was used to allow for comparisons between undiluted freshwater sites and diluted tidal sites; the dilution and subsequent multiplication at higher salinity sites can result in *E. coli* counts over the detection limit, but undiluted sites cannot be given values higher than the detection limit. The total *E. coli* levels at several sites may be far higher than 2419.6 MPN/100 mL.

3.2 Sediment PAH Sampling

Sediment sampling for PAH analysis was conducted at 13 sites for this program (Table 1). Sampling occurred at low tide, typically at the same time as water quality sampling. A plastic corer was used to collect a standardized amount of sediment from each site (2018: n = 1/site, 2019-2020: n = 3/site, 2021: n = 4-6/site, 2022: n = 2-4/site). The corer was cleaned between sites with acetone and deionized water or 5% nitric acid (Figure 3). An operator wore clean powder-free nitrile gloves at each site, and the corer was rinsed in site water before each sample was collected. Each sediment sample was collected from the top 5 cm, placed into a clean glass jar, and frozen. Sediment samples were sent to the Research and Productivity Council of New Brunswick in Fredericton for PAH analysis (detection limit [DL]: 0.01-0.05 mg/kg).

Total PAHs were calculated from the addition of all individual PAHs (17 PAH analytes). Individual PAH values that were lower than the detection limit (0.01-0.05 mg/kg) were reported as half the DL (0.005-0.025 mg/kg). As a result of this, the lowest total PAH concentration possible in this report is 0.085 mg/kg. Blank samples (n = 19) were all reported as lower than the DL for all of the PAHs tested, spike recovery was 95 ± 9% (n = 19), and duplicate samples were within 7 ± 12 % (n = 12).

Figure 3. ACAP staff member cleaning a plastic corer after collecting a sediment sample.

3.3 Biotic Community Sampling

Nekton community sampling (i.e., fish and crustaceans) was conducted monthly at eight sites from May to October between October 2018 and October 2021 (Table 1). Sampling occurred within a two-hour window around low tide using fyke nets and seine nets (Figure 4a and b). Using two types of fishing gear facilitates a more thorough survey of the nekton community by targeting different species and individuals of different sizes. Seine tows were conducted parallel to the shoreline for three minutes at each site. The seine nets had dimensions of 9 x 1.5 m with 9 mm mesh and a central collection bag. All animals collected were identified and counted before being released (Figure 4c). Total body lengths (mm) were measured for up to 30 individuals of each species (Figure 4d). If more than 30 individuals of a species were caught, the remaining individuals were counted but not measured before being released. This was done to reduce animal stress due to handling and time out of their environment. If a large school of one species was caught (i.e., greater than 100 individuals), the group was sub-sampled with a small dip-net to estimate the number of individuals. This was to ensure proper animal care and reduce time out of the water for the animals.

The fyke nets used were 3.7 m long with four hoops and two 3 m long wings, with 38.1 mm mesh in the wings and body, and 22.2 mm mesh in the cod end. A fyke net was installed at low tide and retrieved after approximately 24 hours. The fyke net was returned to the shoreline, and all fish and invertebrates were identified and counted, and lengths were measured for the first 30 individuals. Animals were returned to the water immediately after processing. Salinity and temperature loggers (Star Oddi) were installed with each fyke net as well, recording every 30 minutes for approximately 24 hours. Logged data before net deployment and after net retrieval were removed from the data set. Salinity data is missing from Little River for 2019 because the appropriate logger broke; a new logger was purchased in 2020.

Figure 4. Biotic community collection methods. (**A**) ACAP staff seining at Tin Can Beach; (**B**) ACAP staff retrieving a fyke net after 24 hours; (**C**) ACAP sampling team measuring fish, recording data, and organizing equipment; (**D**) Measuring the total length of a longhorn sculpin on a measuring board.

4. Results & Discussion

4.1 Water Quality

4.1.1 *In-situ* Measurements

The mean values for all water quality measurements are presented in Supplementary Table 1. The sites examined in this program range from marine and estuarine to fully freshwater. The highest mean salinity concentrations were measured at Black Beach (BB) and Mispec Beach (MB), both of which are far outside the Saint John Harbour, while the lowest mean salinity concentrations were mainly at the upstream locations in Marsh Creek and Hazen Creek (Figure 5). There was considerable variation in salinity values across most sites, except for those that were purely marine or freshwater. This demonstrates the strong influence of tidal inflows in the Saint John Harbour and surrounding tributaries. Sites located within rivers (Wolastoq, Kennebecasis River) – such as Spar Cove (SC), Kennebecasis Drive (KD), and Mill Creek (Mill) – experienced a range of salinities due to tidal effects despite their upstream locations. The same was true of sites within smaller creeks that were close to the outflow (e.g., Marsh Creek 2 [MC2], Hazen Creek Mouth [HCM]). At many coastal sites and other sites with a tidal influence (e.g., Spar Cove and Kennebecasis Drive), salinities increased between May and October (Supplementary Figure 1). Conductivity is closely related to salinity and followed similar patterns to those seen in the salinity measurements.

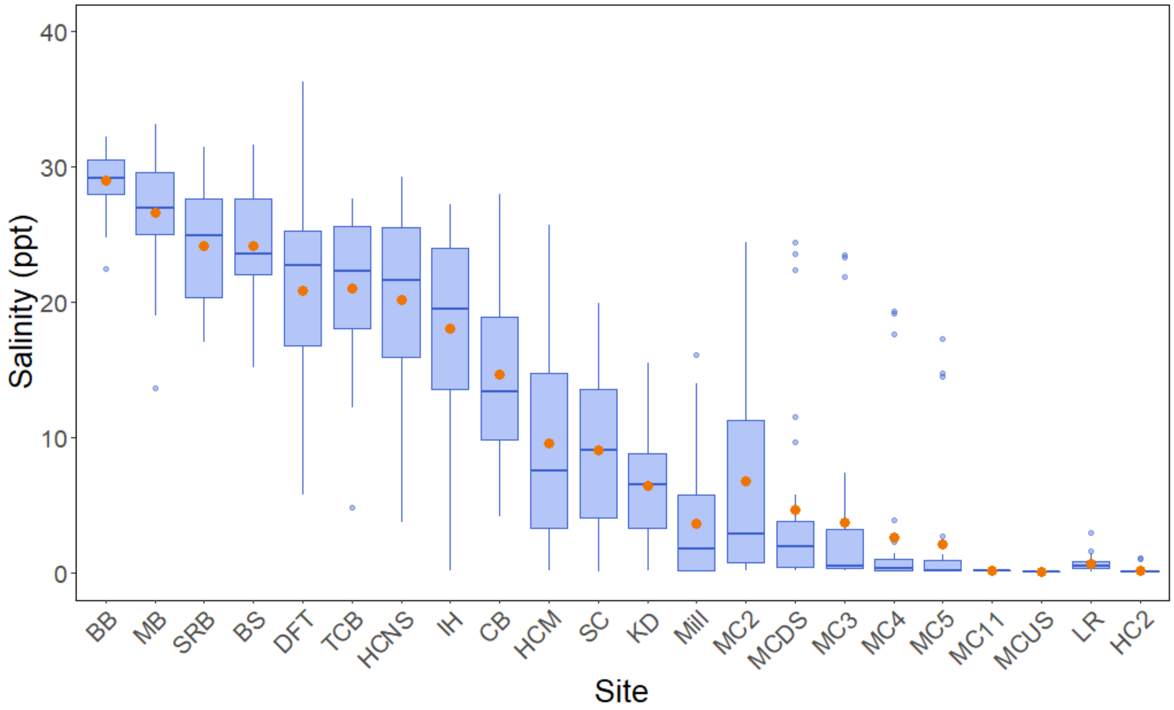

Figure 5. Salinity concentrations (ppt) across 22 sites between 2018 and 2021. The mean concentration at each site is indicated by the orange circles. Outliers are represented by blue circles.

Mean dissolved oxygen concentrations at all sites were suitable for aquatic life (Figure 6). Guidelines to ensure the health of aquatic life have been developed for some water quality parameters by the Canadian Council of Ministers of Ministers of the Environment (CCME). The recommended dissolved oxygen threshold value for the protection of aquatic life is 6.5 mg/L

(Canadian Council of Ministers of the Environment 1999a); all sites had mean concentrations above this threshold. However, some sites had single measurements below this value during the study period. Nearly all sites within the Marsh Creek watershed saw drops in dissolved oxygen at some points, as did Kennebecasis Drive and Little River (LR). Algal growth was frequently observed at these locations, which can lead to decreases in dissolved oxygen as well. The highest dissolved oxygen concentrations across all sites were generally measured in May (10.90 ± 1.96 mg/L) and October (9.12 ± 1.16 mg/L), when temperatures were lowest, while the lowest dissolved oxygen concentrations were typically in August (8.01 ± 1.62 mg/L) at the height of summer (Supplementary Figures 2, 3). While occasional low oxygen levels do not impair the ability of these habitats to sustain life (fish were consistently observed in Marsh Creek and Little River), these low oxygen level events may increase in frequency with pollution and climate change.

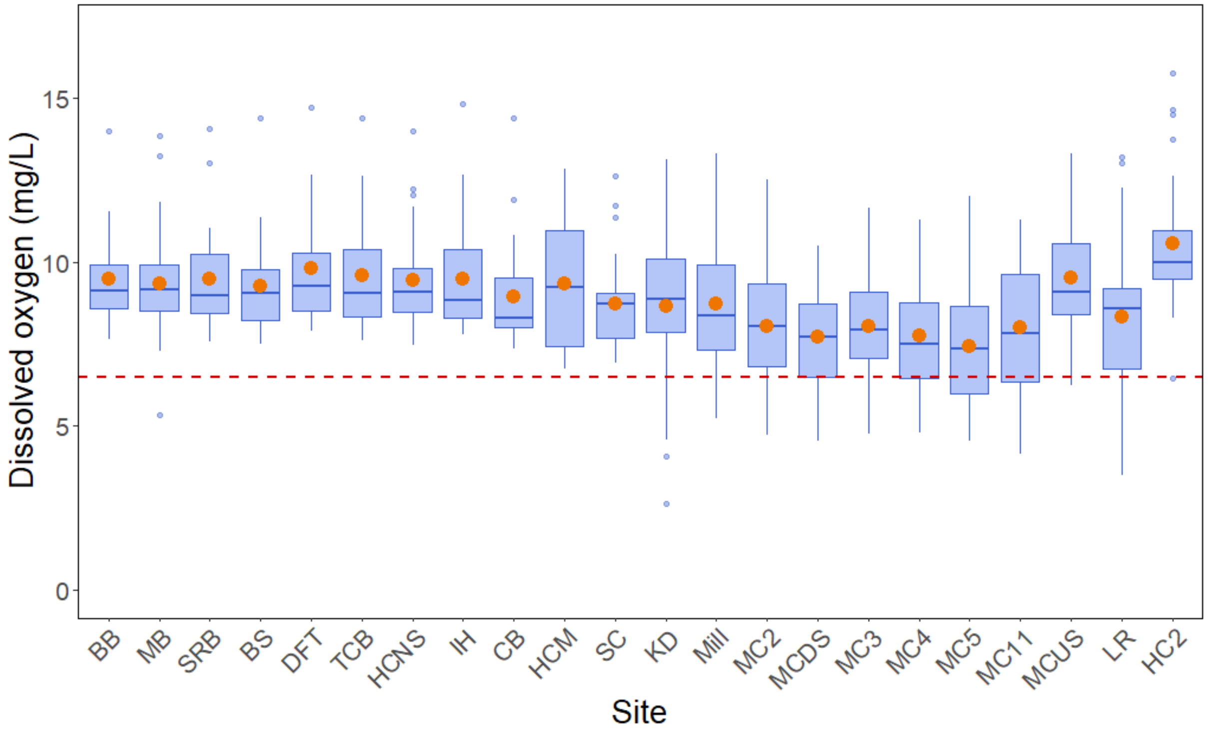

Figure 6. Dissolved oxygen concentrations (mg/L) across 22 sites between 2018 and 2021. The dotted red line indicates the minimum recommended concentration for the protection of aquatic life (6.5 mg/L), and the mean concentration at each site is indicated by orange circles. Outliers are represented by blue circles.

Temperatures below 23°C are considered optimal for juvenile salmonids (Breau et al. 2007). Mean water temperatures at all sites (May – October) remained below 23°C, with none of the sites frequently reaching temperatures that would impair salmonid development (Figure 7). However, high summer water temperatures were measured multiple times at Little River and Kennebecasis Drive, with maxima of 26.4°C and 25.2°C, respectively (Supplementary Figure 4). High temperatures can drive algal growth and lead to decreased oxygen levels, as observed in Figure 6 above. High temperature events can create stressful conditions for aquatic life and have negative impacts on aquatic communities. These two sites appear to the be at increased risk of negative impacts from elevated temperatures.

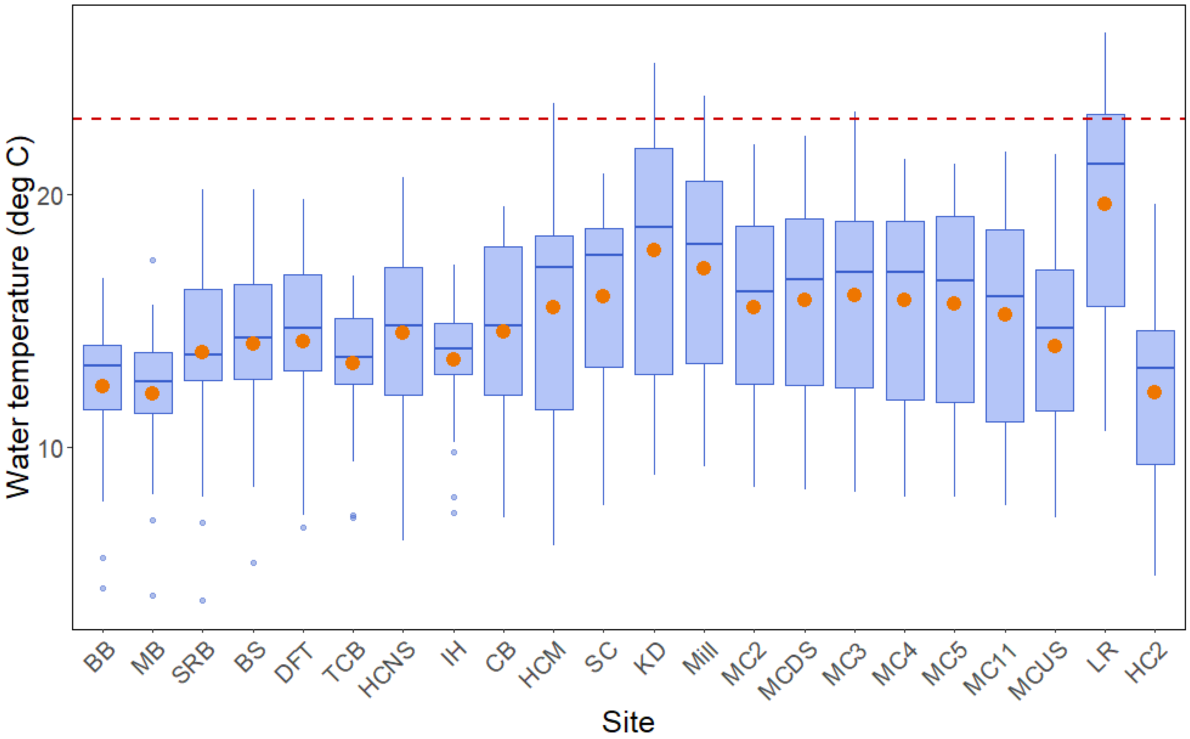

Figure 7. Water temperatures (°C) across 22 sites between 2018 and 2021. The dotted red line indicates the maximum recommended temperature for salmonids (23°C), and the mean temperature at each site is indicated by orange circles. Outliers are represented by blue circles.

The pH values at all sites typically remained within acceptable levels; the guidelines used were a lower limit of 6.5 and an upper limit of 9 (Canadian Council of Ministers of the Environment 1999b). Turbidity does not have a set guideline from the CCME, so we selected 55 NTU as an upper threshold to examine site-specific differences. Turbidity measurements were considerably higher in coastal sites than those within rivers or streams (Figure 8). This is not unexpected and highlights one reason why there is no set guideline; with increased wave action, coastal sites can have naturally high turbidity levels as sediments are continuously moving near shore. These elevated turbidity levels therefore do not necessarily indicate poor water quality because high turbidity is an inherent characteristic of these sites. Elevated turbidity levels at sites within streams/rivers, such as Spar Cove and Little River, are more likely to indicate poor conditions and can be the result of pollution. These sites experienced a small number of high turbidity events over the study period but remained well below a mean value of 55 NTU.

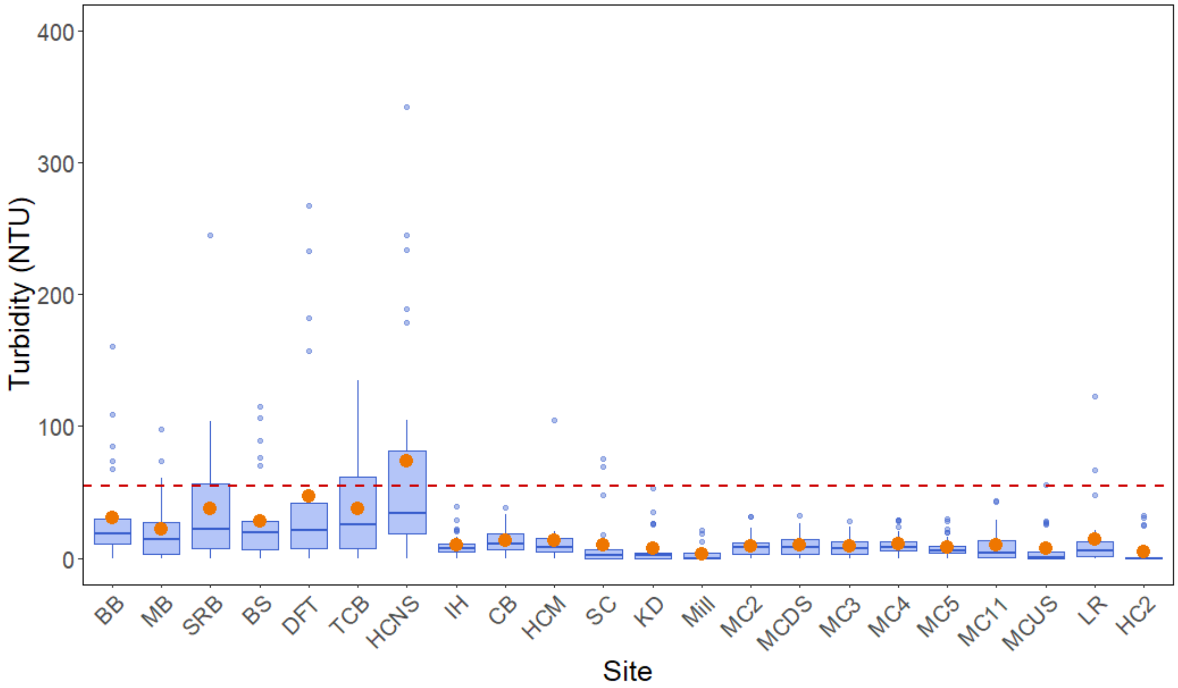

Figure 8. Turbidity (NTU) across 22 sites between 2018 and 2021. The dotted red line indicates the selected threshold (55 NTU), and the mean turbidity at each site is indicated by orange circles. Outliers are represented by blue circles.

The loggers deployed with fyke nets at the eight fishing sites recorded temperature, salinity, and conductivity every 30 minutes during the period of deployment (Table 2). Little River was the warmest and freshest site, while the other sites tended to be cooler and had more variation in salinity.

Table 2. Mean (± SD) values for temperature (°C), salinity (PSU), and conductivity (mS/cm) logged during fyke net deployment at eight fishing sites from 2019 to 2021. Loggers took measurements every 30 minutes. Measurements at Little River only run from 2020 to 2021.

Site	**Temperature (°C) Mean**	**SD**	**Salinity (PSU) Mean**	**SD**	**Conductivity (mS/cm) Mean**	**SD**
Courtenay Bay	13.31	3.10	18.84	6.32	23.33	7.26
Digby Ferry Terminal	12.27	2.88	21.68	6.71	26.09	7.72
Hazen Creek Nearshore	11.83	3.30	24.59	5.42	28.87	6.11
Inner Harbour	12.87	3.01	18.48	7.59	22.68	8.63
Little River	20.64	2.60	0.49	0.30	0.90	0.56
Marsh Creek 2	14.14	3.34	16.26	7.49	21.20	9.25
Spar Cove	16.22	2.35	11.69	5.62	16.02	7.01
Tin Can Beach	12.64	2.88	21.38	5.71	25.94	6.59

These loggers captured fine-scale variation in salinity (Figure 9a) and temperature (Figure 9b) over a 24-hour period. At sites with both freshwater and tidal influences, such as Inner Harbour (IH), the input of cold, high salinity water from the tide is very noticeable.

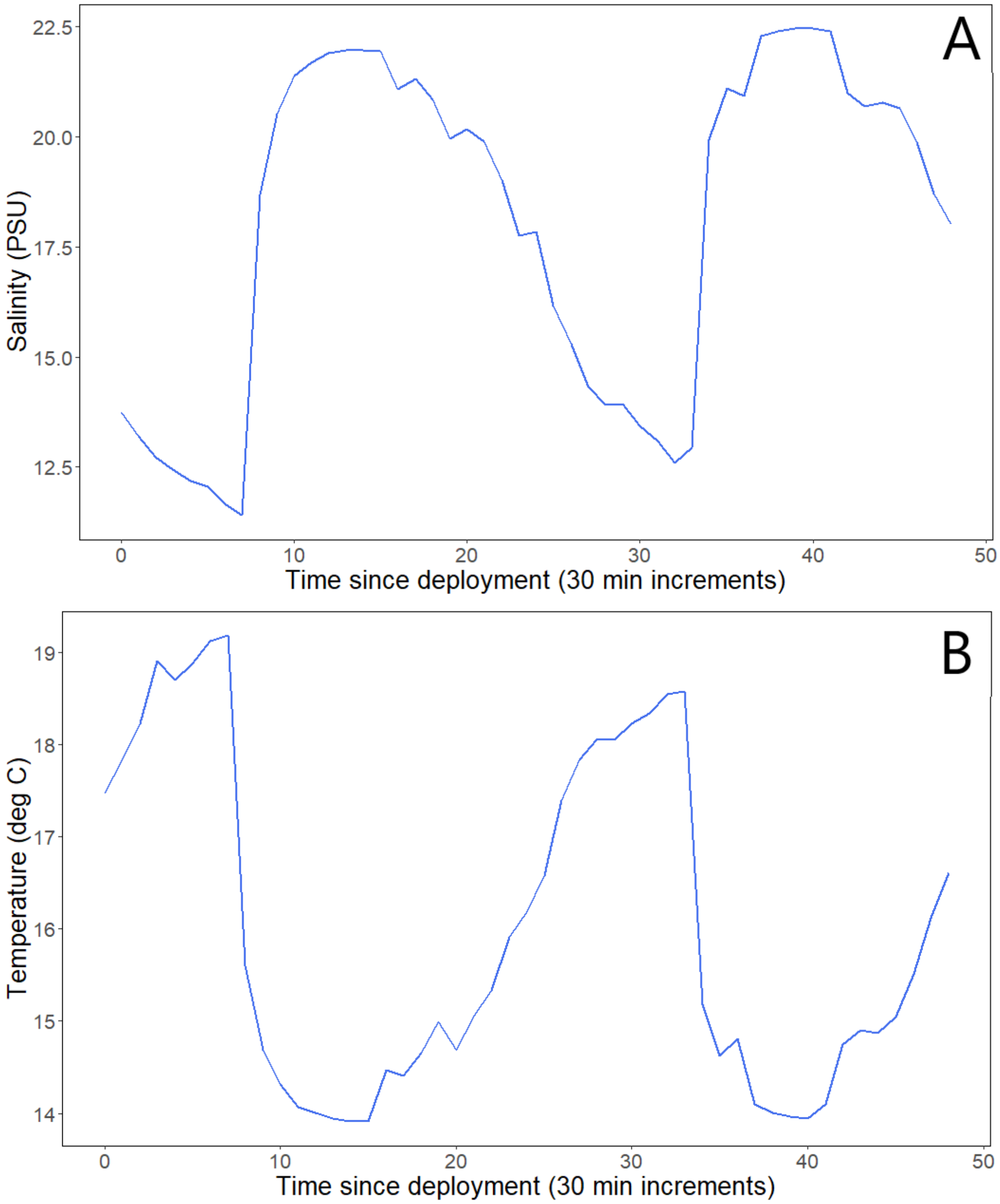

Figure 9. Time series of (**A**) salinity (PSU) and (**B**) temperature (°C) during the period of fyke net deployment (24 hours, 30-minute increments) at Inner Harbour on August 16 and 17, 2021.

4.1.2 Nutrients

Ammonia concentrations varied across sites within the Saint John Harbour. The CCME have reported that most natural waters have total ammonia concentrations below 0.1 mg/L (Canadian Council of Ministers of the Environment 2010); we have taken this as a threshold value above which aquatic life may suffer negative impacts. Mean ammonia concentrations throughout the study period were at or above 0.1 mg/L at 6 sites in the Marsh Creek watershed as well as Little River (Figure 10). At most sites there were occasional measurements of high concentrations with median levels generally remaining quite low. Little River had exceptionally high concentrations compared to all other sites, with a mean concentration of 0.61 ± 0.24 mg/L. This is over four times higher than the next highest mean concentration at Marsh Creek 2 (0.13 ± 0.056 mg/L).

While ammonia concentrations were elevated throughout the Marsh Creek watershed, there was a small decrease at more upstream sites. The highest ammonia levels are at the most downstream site (MC2), and the lowest levels are at the most upstream site (Marsh Creek Upstream, MCUS; 0.068 ± 0.053 mg/L). This pattern suggests that contamination sources may increase at downstream locations and contamination accumulates as water moves downstream. There are several potential contamination sources along Marsh Creek, with multiple commercial and residential developments along the watercourse.

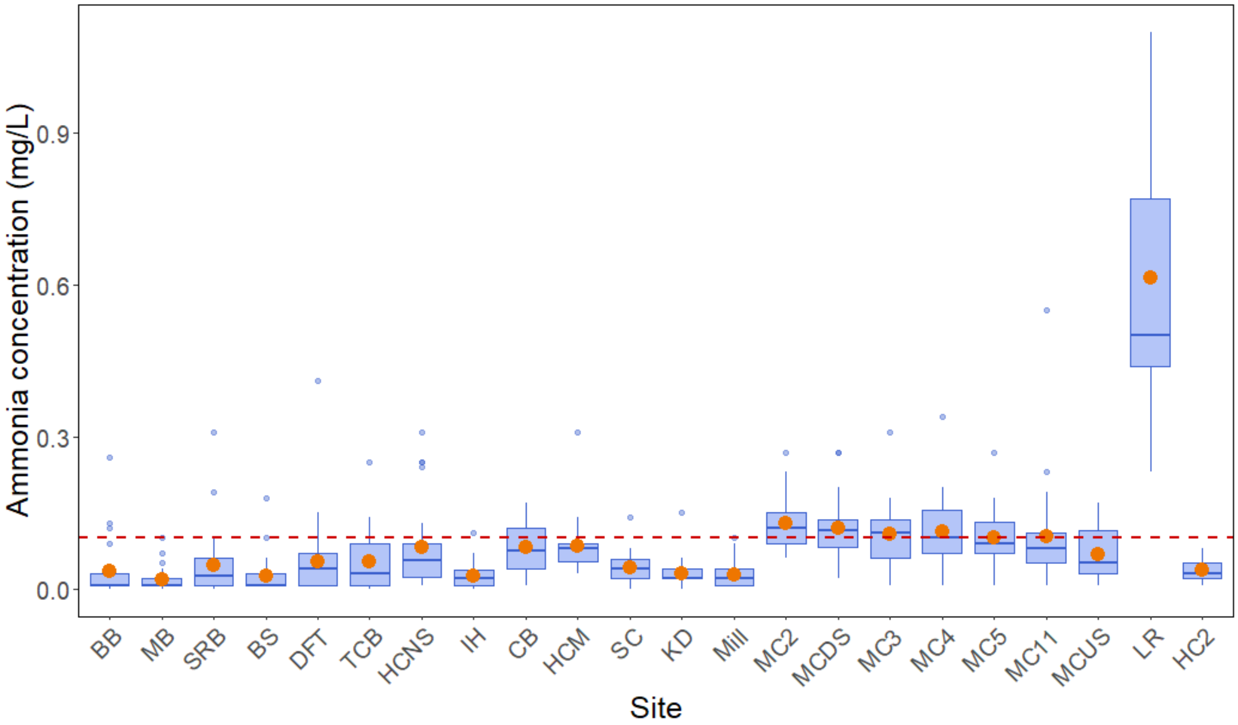

Figure 10. Ammonia concentrations (mg/L) across 22 sites between 2019 and 2021. The dotted red line indicates the recommended upper limit for healthy aquatic life (0.1 mg/L), and the mean concentration at each site is indicated by the orange circles. Outliers are represented by blue circles.

Ammonia concentrations differed significantly across years between 2019 and 2021 (ANOVA, F = 4.91, p = 0.027; Figure 11). Ammonia levels exceeded the threshold (0.1 mg/L) most frequently in 2021 and least frequently in 2020. The elevated levels observed in 2021 may be due in part to sampling errors, as identified in the Methods section above. However, ammonia concentrations regularly exceeded 0.1 mg/L at numerous sites in previous years as well, particularly in Marsh Creek and Little River. There was also a significant effect of site on ammonia concentrations (F = 48.21, p < 0.001); the most contaminated sites were Little River and all Marsh

Creek sites except for Marsh Creek Upstream. No significant differences were observed across months (F = 1.81, p = 0.096; Supplementary Figure 5).

Due to the high ammonia concentrations measured in 2021, no ammonia guidelines were developed to identify generally acceptable limits in the Saint John Harbour specifically. Future monitoring to supplement the data set could allow for a guideline to be developed that will identify when ammonia limits surpass a reasonable threshold.

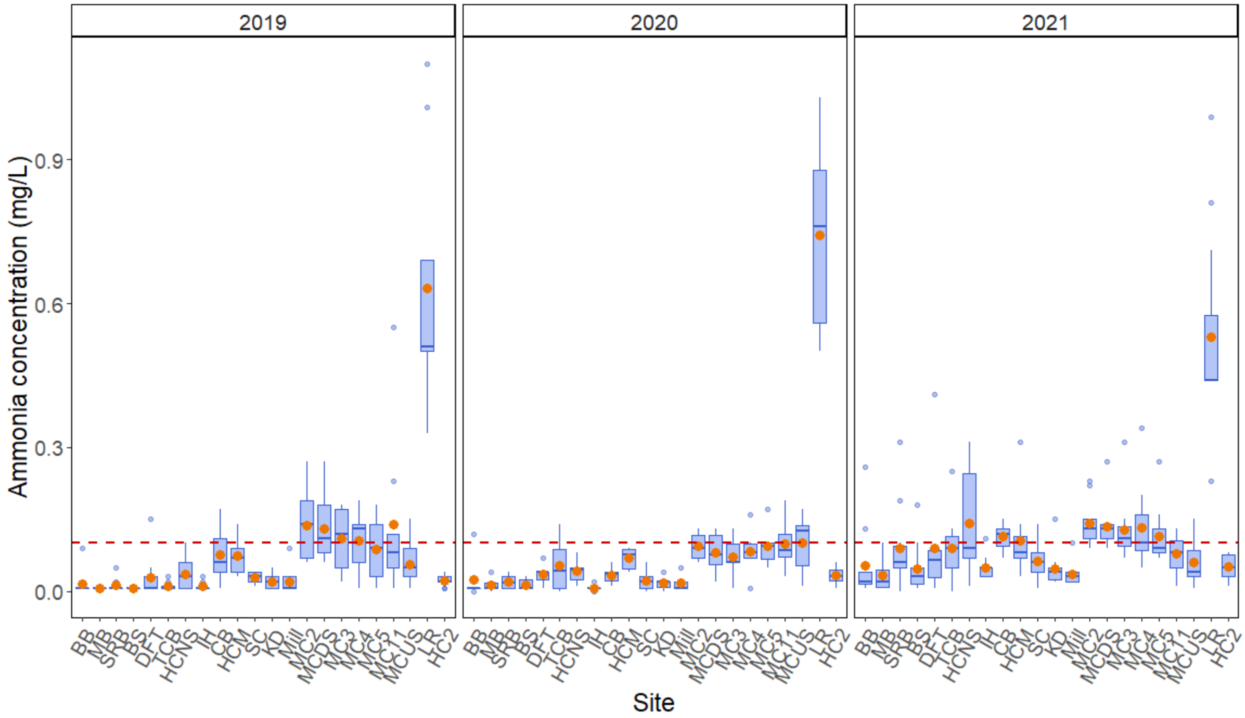

Figure 11. Ammonia concentrations (mg/L) across 22 sites in 2019, 2020, and 2021. The dotted red line indicates the recommended upper limit for healthy aquatic life (0.1 mg/L), and the mean concentration at each site is indicated by the orange circles. Outliers are represented by blue circles.

Phosphate concentrations also varied across sites. Orthophosphate (PO_4^{3-}) and phosphorous (P) were both measured in this study. There is currently no CCME guideline for phosphate levels in aquatic environments, but the United States Environmental Protection Agency (EPA) recommends maximum total phosphate concentrations are kept below 0.05 mg/L or 0.1 mg/L in freshwater streams (US Environmental Protection Agency 1986).

We developed a phosphate guideline for the Saint John Harbour based on the 95th percentile. 95% of orthophosphate concentrations measured throughout the study period were below 0.234 mg/L; this was taken as an upper limit threshold. The average of the 95th percentile is 0.0728 mg/L, which we took as a threshold below which phosphate levels are considered acceptable. These thresholds are quite high compared to the US EPA recommendations, in large part due to the extremely high concentrations measured at Little River; this site had concentrations 7 times higher (0.77 ± 0.66 mg/L) than the next highest site

(Courtenay Bay, 0.11 ± 0.042 mg/L; Figure 12). Additional thresholds can be developed based on the 90th percentile or additional percentiles, depending on the preferences of managers.

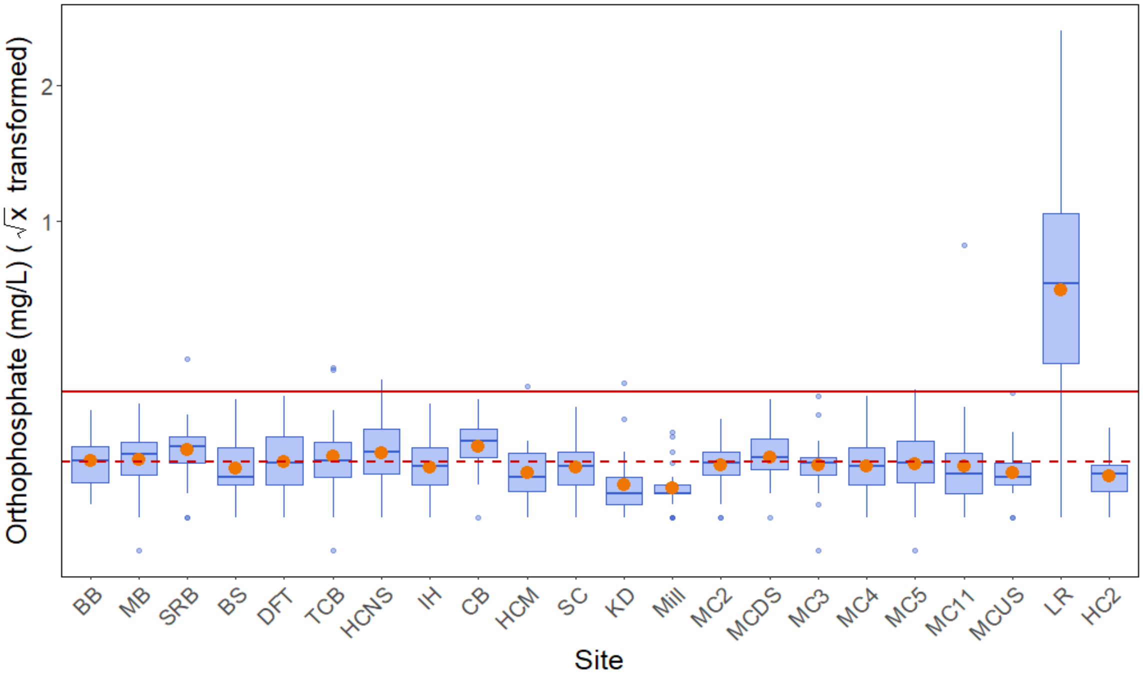

Figure 12. Square root transformed orthophosphate concentrations (mg/L) across 22 sites between 2019 and 2021. The solid red line indicates the 95th percentile (0.234 mg/L), the dotted red line indicates the average of the 95th percentile (0.0728 mg/L), and the mean concentration at each site is indicated by the orange circles. Outliers are represented by blue circles.

4.1.3 Fecal Coliforms (*Escherichia coli*)

Many sites in and around the Saint John Harbour had elevated *E. coli* concentrations during the study period. Mean concentrations exceeded the recommended guideline for recreational use (200 MPN/100mL; Canadian Council of Ministers of the Environment 1999c) at 14 sites, with the highest concentrations mainly within the Marsh Creek watershed and Courtenay Bay (Figure 13). Within Marsh Creek, the greatest *E. coli* levels were detected at the most downstream sites, Marsh Creek 2 (2271 ± 379 MPN/100 mL) and Marsh Creek Downstream (2181 ± 472 MPN/100 mL). As described above, it appears that contamination accumulates most at downstream locations within Marsh Creek. Other sites with elevated *E. coli* counts include Kennebecasis Drive (very shallow, plenty of waterfowl), Spar Cove (SC; receives stormwater/sewer overflow inputs), Hazen Creek Mouth, and Hazen Creek Nearshore (HCNS; both Hazen Creek Sites are near a sewage treatment facility).

The lowest *E. coli* levels were generally measured at coastal sites outside of the industrial core of the Saint John Harbour, namely Black Beach, Mispec Beach, Saint's Rest (SRB), Bayshore (BS), and Digby Ferry Terminal (DFT). These sites are located away from industrial and municipal influences, and also benefit from being coastal sites with more water movement. With few exceptions, sites within the Saint John Harbour itself and nearby watercourses had very high *E. coli* concentrations, indicating persistent contamination issues. The highest contamination levels were measured in the summer months (Supplementary Figures 6, 7), perhaps due to increases in rainfall events or sewage overflows. In addition, many sites that normally have very low *E. coli* levels (i.e., Black Beach, Hazen Creek Nearshore, etc.) experienced elevated levels in July 2021. It remains unclear whether some or all of these measurements are the result of errors in sampling/analysis, or if conditions were particularly poor at that point in time due to rainfall, overflows, or some other contamination source. Because of this event, median *E. coli* concentrations are also presented in Supplementary Table 1 to better illustrate the typical *E. coli* levels measured at each site.

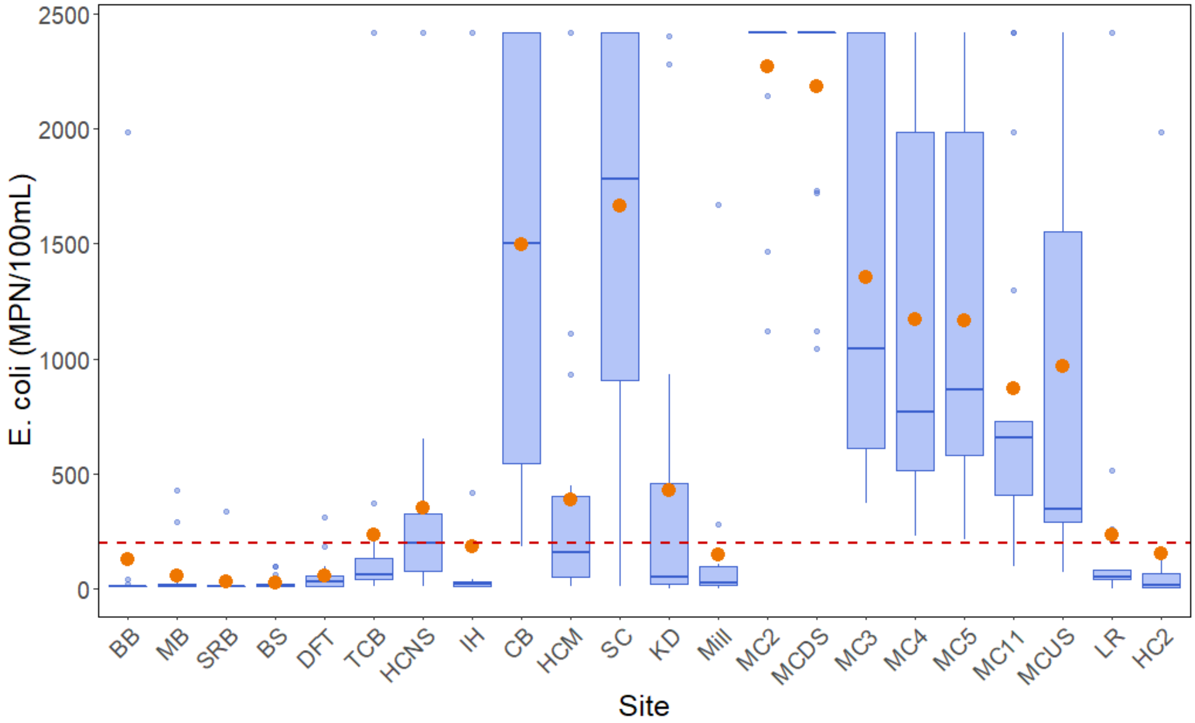

Figure 13. *E. coli* concentrations (MPN/100mL) across 22 sites between 2020 and 2021. The dotted red line indicates the recreational limit (200 MPN/100mL), and the mean concentration at each site is indicated by the orange circles. Outliers are represented by blue circles.

4.2 Sediment PAHs

Total PAH concentrations varied across Harbour sites from 2018 to 2022, with a number of sites exceeding the disposal at sea limit (Figure 14). Mean concentrations exceeded this limit at Digby Ferry Terminal, Courtenay Bay, Little River, Spar Cove, Tin Can Beach, and Marsh Creek. Mean concentrations at other sites remained below the limit; the sites furthest from the Saint John Harbour (Black Beach, Bayshore, Mispec, Saint's Rest) consistently had PAH concentrations below the detection limit of 0.01 mg/kg.

The overall mean of total PAH concentration measured from 2018 to 2022 was 5.63 ± 18.42 mg/kg. This level is high compared to other Saint John Harbour PAH studies, though the extremely high PAH concentrations in Marsh Creek are a major contributor to this high average. A study by Zitko (1999) sampled sediments from industrial areas around the Saint John Harbour from 1996-1999 and found an average total PAH concentration of 1.30 mg/kg. The average total PAH concentration found in our study is more than 4 times higher than that found by Zitko, despite that study having sites centered around industrial areas. Van Geest et al. (2015) found average concentrations of 0.18 and 0.14 mg/kg at reference sites in the inner and outer Harbour, respectively, which are 31 - 40 times lower than the average of sediments from the present study.

The average value from the present study is also higher than the recommended total PAH threshold in sediments for the protection of aquatic life (1.7 mg/kg; Buchman 2008), and the disposal at sea limit (2.5 mg/kg; Canadian Council of Ministers for the Environment 1999d). Van Geest et al. (2015) also identified a range of expected values for total PAH concentrations at reference sites in the Harbour (0 - 1.9 mg/kg). The range in total PAH concentrations across sites from the present study far exceeds that range at 0.085 – 167.32 mg/kg, though it is worth noting that we could not reliably measure very low PAH concentrations, and the true lower limit at our sites is likely below 0.085 mg/kg. When considering the extreme PAH values in the heavily contaminated Marsh Creek, using the median value of 0.46 mg/kg might be more representative of the total PAH concentrations generally measured in the Harbour. Almost half the sites had mean total PAH concentrations higher than the reference range identified for the Harbour (Van Geest et al., 2015), with the highest concentrations in decreasing order in Marsh Creek > Spar Cove > Tin Can Beach > Little River > Digby Ferry Terminal > Courtenay Bay (Supplementary Table 2).

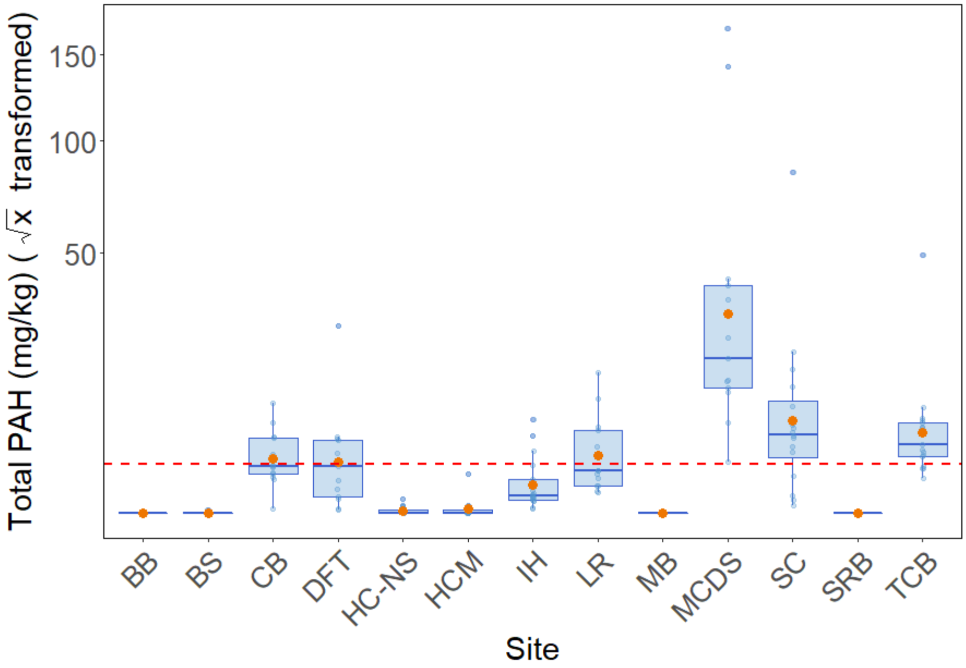

Figure 14. Square root transformed total PAH concentrations (mg/kg) across 13 sites between 2018 and 2022. The disposal-at-sea limit (2.5 mg/kg) is indicated by the red dotted line, and mean totals for each site are indicated by orange circles.

The total PAH concentrations at Marsh Creek ranged from 2.64 – 167.32 mg/kg, indicating that this site consistently has PAH concentrations above the disposal-at-sea limit, and concentrations were generally much higher than this threshold. These extreme values are concerning considering the toxicity thresholds for aquatic life (1.7 mg/kg total PAHs). It should be noted that only a small portion of the full concentration of PAHs found in sediments is available for uptake by biota (Cornelissen 1999). This means that the heavy contamination seen at some sites within the Harbour may not significantly affect organisms in the water column such as fish. This does not preclude species from being affected by other sources of contamination, however, and extremely high PAH levels such as those in Marsh Creek may still impact organisms, particularly those in the benthos.

The contamination observed in Marsh Creek is partially the result of a historic lumber yard that was situated on the banks of the stream where logs were treated with creosote (a preservative made from a mixture of PAHs) and allowed to drip into the water. Canada Post is currently occupying the contaminated land, and a retaining wall has been constructed that acts as a barrier theoretically preventing more creosote from entering the stream. However, it is estimated that 10,000 m^3 of creosote-soaked sediment remains in the watercourse to this day. This creosote contamination is situated in the tidal portion of the stream and has the potential to migrate further into the Harbour with the moving tides and water flow. Other Harbour sites that have total PAH concentrations above the disposal at sea limit may have influences from point sources (i.e., refueling boats and stormwater outflows) or from nonpoint sources (i.e., road-runoff, atmospheric deposition, inputs from marine traffic).

The most prominent PAH analytes were fluoranthene, pyrene, and phenanthrene, which together made up 49.56% of the total (Table 3). Van Geest et al. (2015) also found that phenanthrene, fluoranthene, and pyrene made up most of the Harbour reference site total PAH concentration. Fluoranthene, pyrene, and phenanthrene are all present at levels greater than the CCME interim sediment quality guidelines (ISQGs; Canadian Council of Ministers of the Environment 1999d). The guidelines are 0.11, 0.15, and 0.087 mg/kg for fluoranthene, pyrene, and phenanthrene, respectively, and the mean ± SD for each PAH in this study was 1.12 ± 5.23 mg/kg (fluoranthene), 0.66 ± 2.38 mg/kg (pyrene), and 0.91 ± 3.56 mg/kg (phenanthrene). Bioavailability of PAHs is related to molecular weight, with low-weight PAHs more easily taken up by organisms because they do not sink out of the water column as readily (Vagi et al. 2021). The most abundant PAH analyte in the Saint John Harbour, fluoranthene, has a high molecular weight (Canadian Council of Ministers of the Environment 1999d); this may prevent organisms from being negatively affected by PAHs to some extent.

Table 3. The percent composition of total PAHs (sum of all PAH analytes) measured across 13 coastal Saint John Harbour sites from 2018 to 2022.

PAH Analyte	%
Fluoranthene	21.18
Pyrene	16.28
Phenanthrene	12.10
Benz(a)anthracene	7.72
Benzo(b+j)fluoranthene	7.49
Chrysene/Triphenylene	6.63
Benzo(a)pyrene	5.98
Anthracene	4.43

Benzo(e)pyrene	3.91
Indeno(1,2,3-c,d)pyrene	3.24
Benzo(k)fluoranthene	2.88
Benzo(g,h,i)perylene	2.83
Fluorene	1.84
Acenaphthene	1.09
Naphthalene	1.04
Dibenz(a,h)anthracene	0.85
Acenaphthylene	0.51

4.3 Biotic Communities

Beach seining and fyke netting was conducted monthly at 8 fishing sites between 2018 and 2021, and a total of 35,213 fish and invertebrates were caught, representing 34 species. Spar Cove had the greatest total catch (11,599 individuals), with the majority of these individuals being Atlantic silverside (*Menidia menidia*), while Little River had the lowest total catch with 328 individuals (Figure 15). Atlantic silverside was the most frequently caught species (14,640 individuals), followed closely by sand shrimp (*Crangon septemspinosa*; 14,224 individuals) and then by threespine stickleback (*Gasterosteus aculeatus*; 2320 individuals) and Atlantic tomcod (*Microgadus tomcod*; 2045 individuals). The most consistently sampled species were Atlantic silverside and sand shrimp, which were the only species caught at all eight sites (Figure 16).

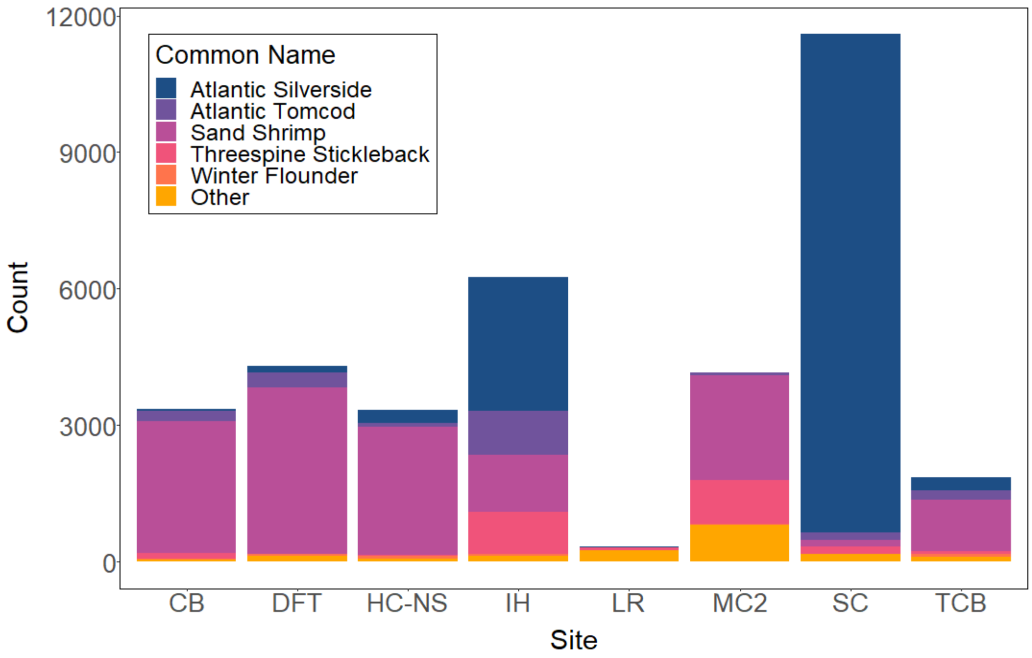

Figure 15. Total catch across eight fishing sites between 2018 and 2021. Less abundant species (29 species) are grouped into an “Other” category.

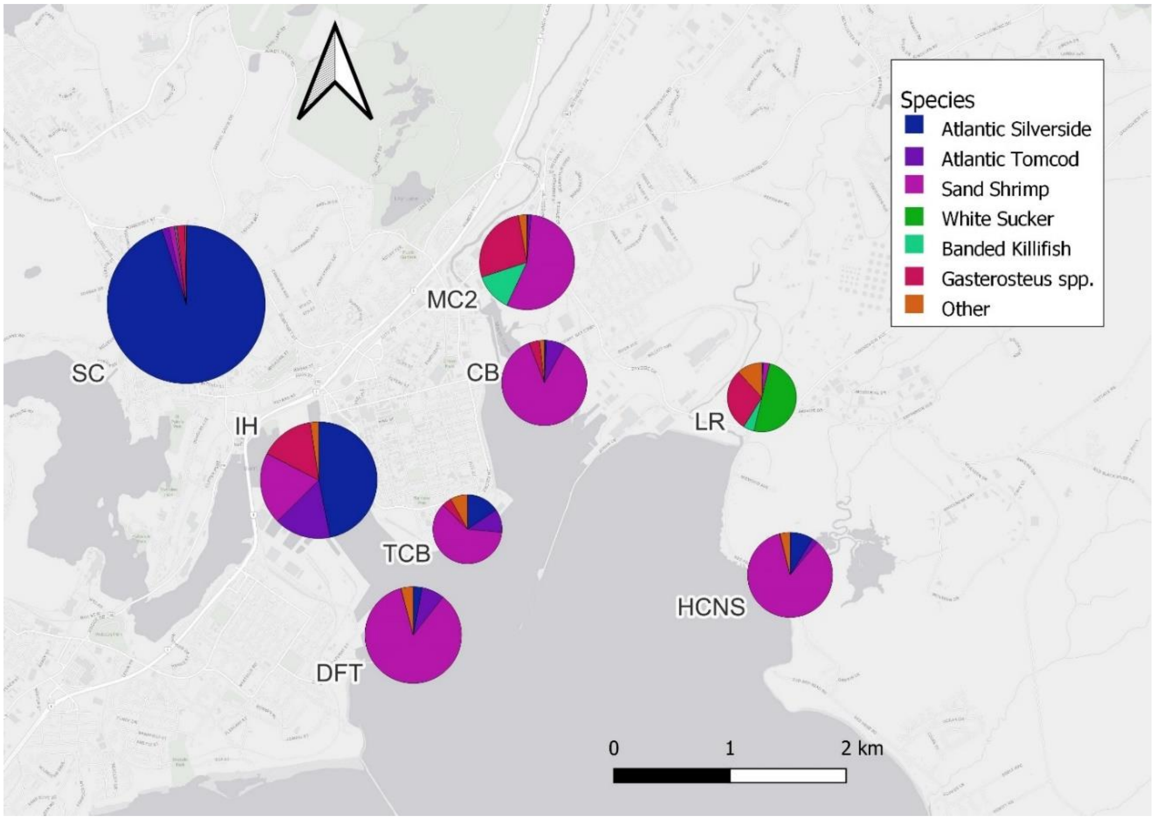

Figure 16. Map with pie charts of relative species abundances at eight fishing sites (2018 – 2021). "*Gasterosteus* spp." includes 4 stickleback species, and "Other" includes 26 other species. The size of each pie chart is relative to the total number of species caught; the greatest number of individuals were caught at Spar Cove, and the fewest at Little River.

The biotic communities studied in this project varied in species abundance and diversity (Table 4). While the number of species observed at each site was relatively similar (13 – 17), the diversity across sites differed based on species abundances and evenness. Species richness considers not only the number of species observed but also the relative abundances of each of those species. As noted above, Spar Cove had the greatest abundance while Little River had the lowest abundance. However, species diversity and evenness at Spar Cove was much lower than at Little River, as well as all other sites. This is due to the outsized effect of extremely high silverside numbers at this site; this species dominates the community at Spar Cove such that other species make up a relatively small amount of the total diversity. The same is true at Courtenay Bay, Digby Ferry Terminal, and Hazen Creek with sand shrimp, though to a lesser extent.

The species assemblages at Inner Harbour, Little River, Marsh Creek 2, and Tin Can Beach had more even distributions of species, with no single species dominating the community as much as at the other sites. This resulted in higher diversity and evenness indices and suggests that these sites can support more species types. However, Little River and Marsh Creek are the two most polluted locations in the Harbour that we examined for this project, and Little River still had far fewer individuals than other sites. The persistent contamination issues at Marsh Creek do not seem to have impacted the watershed's ability to support aquatic life. This is an encouraging sign given the efforts in the past decade to rehabilitate Marsh Creek, but there is still more work to be done to make sure that this watershed can maintain healthy aquatic communities in the long-term.

Table 4. Diversity, richness, and evenness measures for each fishing site across the period between 2018 and 2021. Richness is the number of species observed at each site and abundance is the number of individuals caught. The Shannon-Weiner Index (H') is a measure of species diversity within a community based on the number of species and evenness of abundance. Simpson's Index (λ) is another diversity index that measures dominance, taking into account number of species present as well as relative abundances. Pilou Evenness (J) compares true diversity to the maximum possible diversity measure.

Site	Richness	Abundance	Shannon-Weiner Index (H')	Simpson's Index (λ)	Pilou Evenness (J)
Courtenay Bay	17	3353	0.601	0.251	0.0886
Digby Ferry Terminal	15	4295	0.637	0.267	0.0984
Hazen Creek Nearshore	17	3345	0.638	0.271	0.0957
Inner Harbour	17	6266	1.40	0.694	0.245
Little River	16	328	1.73	0.703	0.254
Marsh Creek 2	15	4165	1.30	0.619	0.229
Spar Cove	13	11599	0.280	0.0964	0.0376
Tin Can Beach	15	1864	1.33	0.591	0.218

A total of 1447 individuals were caught in fyke nets, while 33,768 individuals were caught in seine nets (Figure 17). Fyke nets target larger animals than seine nets, so there are fewer but larger individuals collected with this method. Supplementary Table 3 summarizes the fyke net collection data across all sites and years of collection. There were 23 species collected in the fyke nets throughout this program. Seine nets target smaller and slower moving animals compared to the fyke nets so there are typically many but smaller individuals collected with this method. Supplementary Table 4 summarizes the seine net collection data across all sites and years of collection. There were 26 species collected in the seine nets from 2018 - 2021.

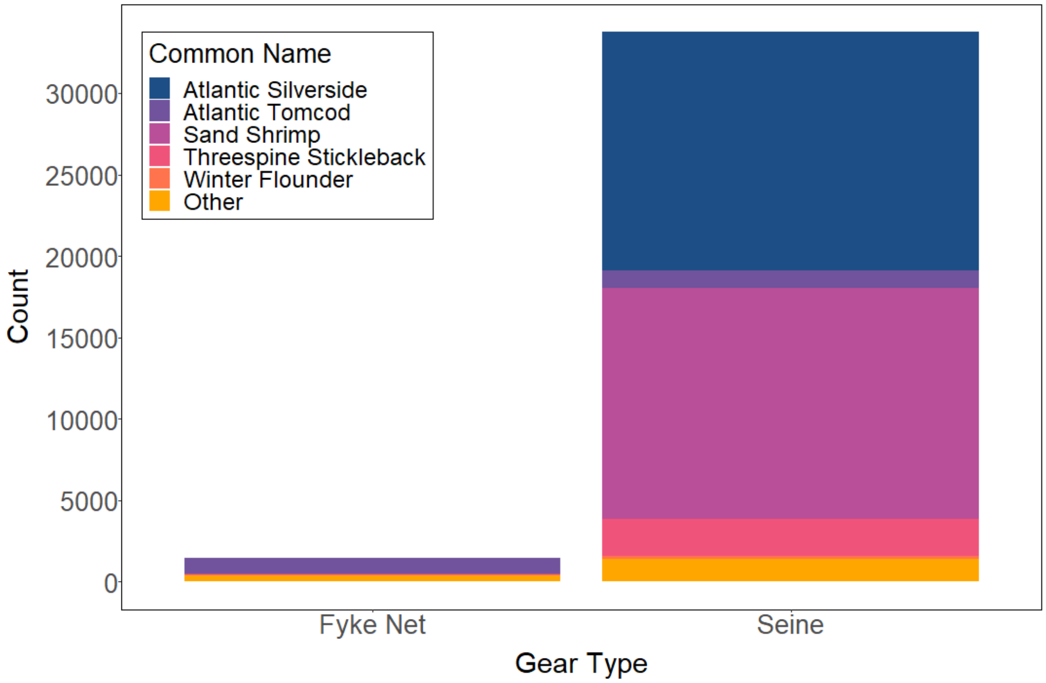

Figure 17. Total catch by gear type between 2018 and 2021. Less abundant species are grouped into an “Other” category.

The most abundant and ubiquitous species sampled in this program were Atlantic silverside, sand shrimp, and Atlantic tomcod. These three species were examined in greater detail to identify temporal and spatial patterns in distributions and lengths. Data from 2018 were removed from analysis because data was only collected in September and October; therefore, only the three full field seasons (May – October) from 2019 to 2021 were analyzed.

4.3.1 Atlantic Silverside (*Menidia menidia*)

Length frequencies of silverside showed significant differences across years (ANOVA, F = 4.87, p = 0.028; Figure 18), months (F = 58.49, p < 0.001; Figure 19) and sites (F = 26.23, p < 0.001). The largest fish were observed outside of the summer months (July, August), perhaps due to summer spawning events resulting in more juveniles during the summer. There was also a significant interaction between month and year (F = 9.46, p < 0.001).

There were significant differences in the number of silversides observed across sites (F = 3.77, p < 0.01) and years (F = 5.38, p = 0.024), but not months (F = 1.08, p = 0.38). Differences across sites are not surprising given the very high abundances of silverside at Spar Cove and their near absence from freshwater sites. Abundances at Spar Cove in 2019 were higher than any other year (Supplementary Table 4); this may be due to favourable conditions in that year, or random chance during sampling.

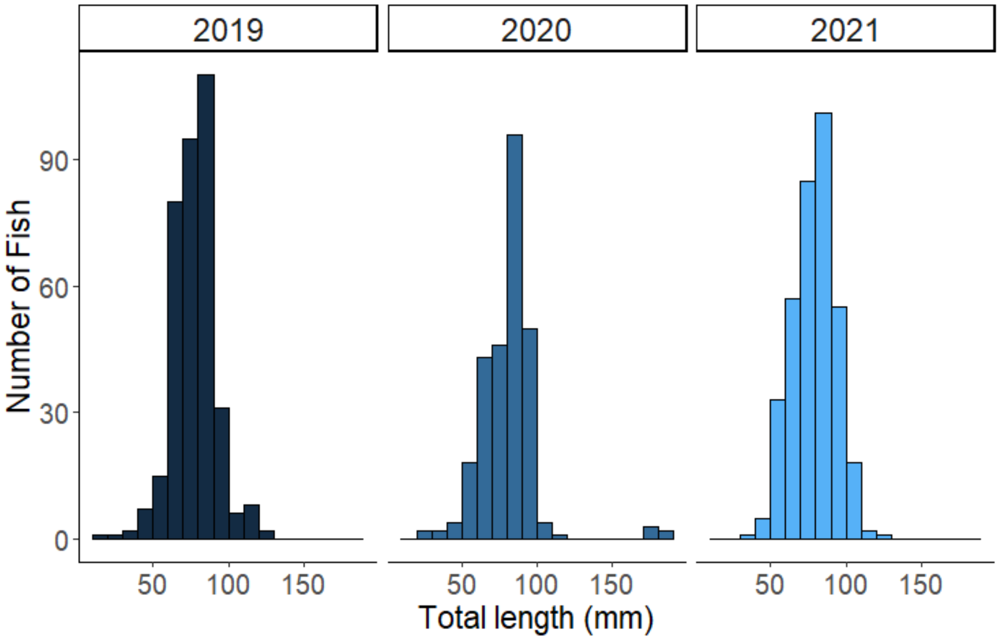

Figure 18. Length frequency distribution (total length, mm) of Atlantic silverside (*Menidia menidia*) pooled across all fishing sites for each full study year (2019 - 2021).

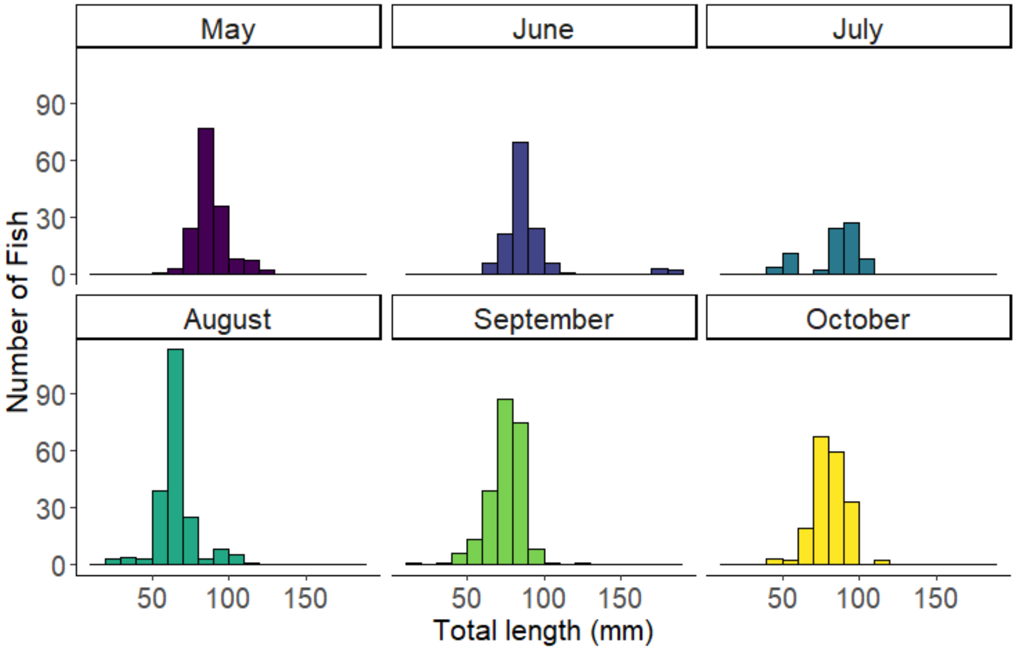

Figure 19. Length frequency distribution (total length, mm) of Atlantic silverside (*Menidia menidia*) pooled across all fishing sites for each study month (May – October).

4.3.2 Sand Shrimp (*Crangon septemspinosa*)

Sand shrimp lengths differed significantly across years (ANOVA, F = 15.47, p < 0.001) and months (F = 70.49, p < 0.001), with a significant interaction between years and months (F = 7.19, p < 0.001). The largest shrimp were primarily caught in June/July of 2019 and 2020. Lengths also differed significantly across sites (F = 41.49, p < 0.001; Figure 20). Shrimp were significantly larger at Hazen Creek and Marsh Creek; this may be due in part to differences in measurement methodology across years.

Shrimp abundances also differed across sites (F = 2.38, p = 0.026), but not years or months. Sand shrimp appear to be present in similar numbers throughout the sampling season (May – October), with little to no seasonal effect during this time period. Sand shrimp do not occur frequently in Little River, potentially due to a combination of its freshwater conditions and high nutrient levels. The effect of pollution on this species is unclear, however, because they are found relatively frequently in Marsh Creek, which is also highly polluted with fecal bacteria, nutrients, and PAHs.

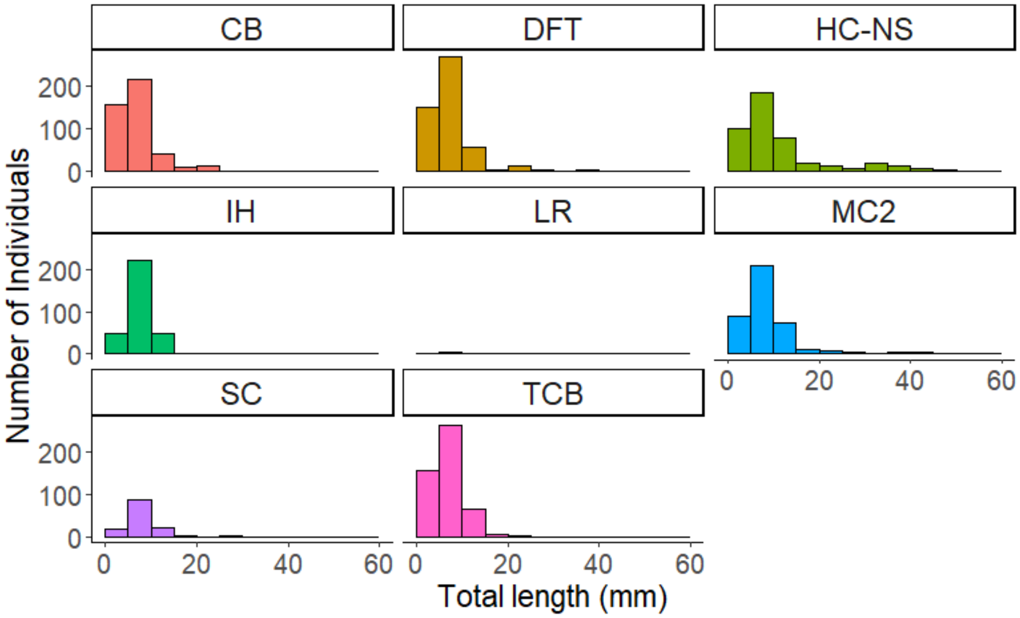

Figure 20. Length-frequency distribution (carapace length, mm) of sand shrimp (*Crangon septemspinosa*) at each fishing site across years (2019 - 2021).

4.3.3 Atlantic Tomcod (*Microgadus tomcod*)

Atlantic tomcod lengths were significantly related to gear type, year, month, and site. The significant effect of gear type (ANOVA, F = 1560.22, p < 0.001) was the result of differences in the sizes targeted by the two types of gear used. Small, juvenile tomcod were caught almost exclusively in seine nets, while larger tomcod with a wider size distribution were caught in fyke nets. Adults were caught more frequently overall. There was also a significant effect of site on the length frequencies of tomcod (F = 56.01, p < 0.001; Figure 21).

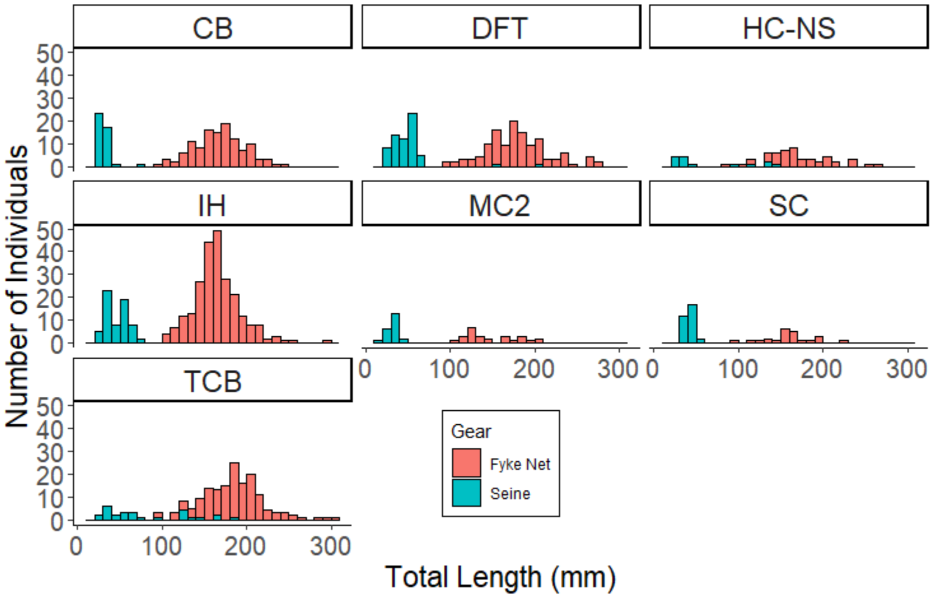

Figure 21. Length-frequency distribution (total length, mm) of Atlantic tomcod (*Microgadus tomcod*) by gear type at each fishing site across years (2019 - 2021).

There was a significant interaction between month and year (F = 7.21, $p < 0.001$). The number of fish caught was also significantly different across gear types (ANOVA, F = 14.14, $p < 0.001$) and sites (F = 2.61, $p < 0.1$). The site with the most tomcod was Inner Harbour, followed by Tin Can Beach, Courtenay Bay, and Digby Ferry Terminal. The more freshwater sites, Marsh Creek 2 and Spar Cove, had the lowest abundances, though they did still support a number of juveniles. Little River did not have any tomcod, likely because it is almost purely freshwater. There was a dramatic increase in juvenile catch in 2021 (Figure 22). As seen above, these juveniles were caught in high abundance at several sites, not just a single location.

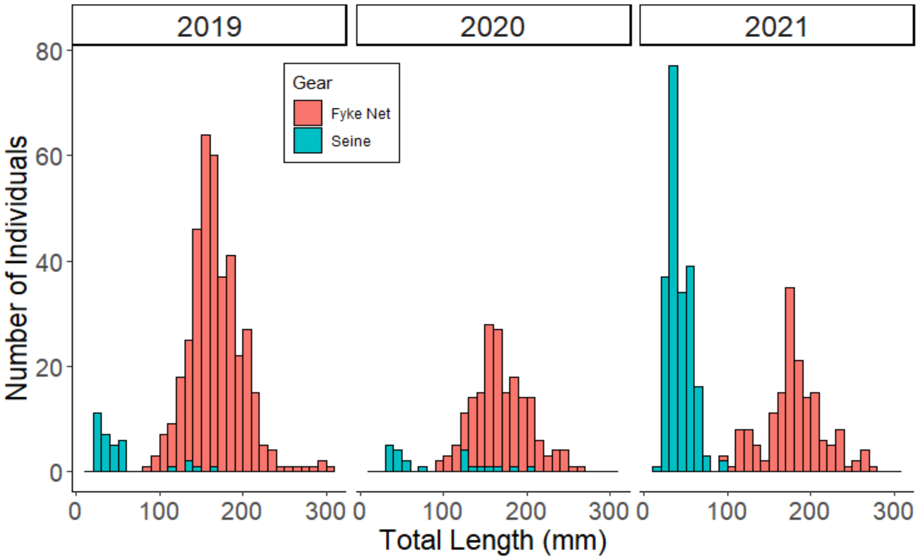

Figure 22. Length frequency distribution (total length, mm) of Atlantic tomcod (*Microgadus tomcod*) pooled across all fishing sites for each full study year (2019 - 2021) and gear type.

Juvenile tomcod were caught almost exclusively in June and July (Figure 23). This is likely a seasonal event that was particularly successful in 2021 (see above), with adults either spawning nearshore or juveniles moving closer to shore during these summer months. The patterns seen in these data indicate potential population cycle dynamics or changes in environmental conditions that would benefit from increased monitoring and study.

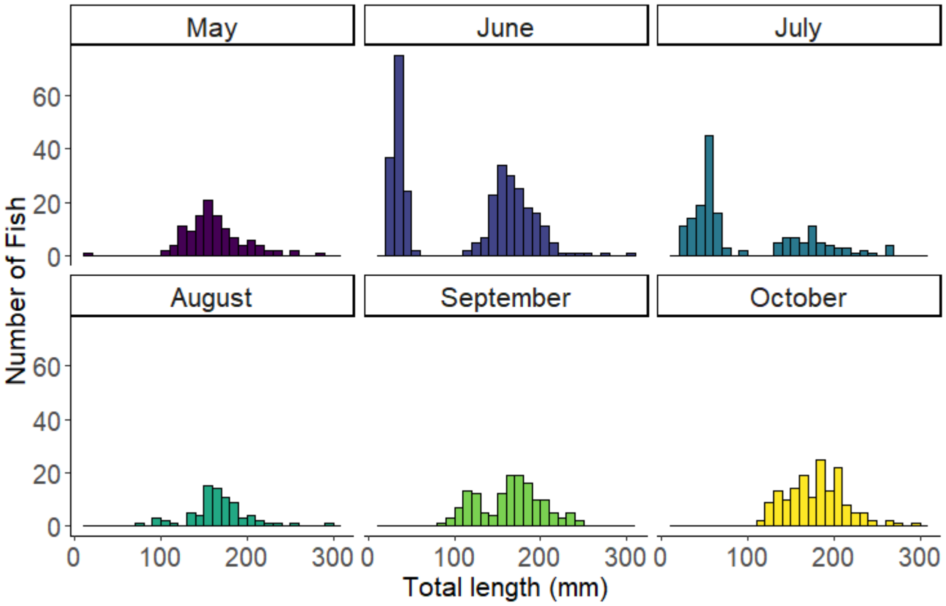

Figure 23. Length frequency distribution (total length, mm) of Atlantic tomcod (*Microgadus tomcod*) pooled across all fishing sites for each study month (May – October).

5. Conclusions and Recommendations

5.1 Water Quality

During this program, 22 sites in and around the Saint John Harbour were sampled for a range of water quality parameters. Out of these sites, 13 were also sampled for sediment PAHs and 8 were sampled for fish communities. Overall, most sites outside of Marsh Creek and Little River had acceptable water quality. Marsh Creek/Courtenay Bay and Little River are sites with known historic contamination from industrial and/or municipal effluents. Conditions within these sites may become more detrimental to aquatic life in the future as a result of climate change and further pollution. Temperatures in Little River reach higher maxima than other sites in this study, and the extremely high nutrient concentrations may contribute to algal growth and other processes that can cause declines in dissolved oxygen. Other sites with moderate amounts of pollution, like Kennebecasis Drive, may also deteriorate without action to reduce contamination and/or temperature increases.

Phosphate guidelines were developed based on the 95th percentile of measurements taken during this project. These thresholds may be used in future studies to evaluate whether phosphate levels are elevated in the Saint John Harbour. Based on these thresholds, mean phosphate concentrations at most sites are generally below or close to acceptable levels, with the notable exception of Little River. Little River concentrations were 7 times higher than the next most polluted site; a similar pattern was observed with ammonia, though ammonia concentrations were also quite high in the Marsh Creek watershed. Ammonia measurements tended to be higher in 2021 than in previous years, perhaps due in part to issues with the blank samples used for analysis. Further monitoring is recommended to elucidate whether ammonia is actually increasing throughout the region and to generate more data that can be used to develop threshold values such as those developed for phosphate.

Mean *E. coli* levels exceeded the recreational guideline (200 MPN/100 mL) at 14 out of 22 sites, which is a concerning trend. The highest concentrations were measured in the Marsh Creek watershed (including Courtenay Bay at the outflow) and Spar Cove. Marsh Creek historically had even higher fecal bacterial counts as the result of raw sewage entering the watercourse. Restoration efforts have improved conditions somewhat since the cessation of raw sewage dumping in 2014, but further remediation or control measures appear to be necessary to reduce fecal bacteria levels within the stream and limit further contamination. For example, there may be stormwater/sewer overflow issues that need to be addressed by the City of Saint John.

Water quality throughout the Harbour can be monitored using methods previously used by ACAP Saint John for other water quality monitoring projects (ACAP Saint John 2021); a water quality index is a useful tool for comparing aquatic health across spatial and temporal scales. Water quality issues such as those observed in Marsh Creek and Little River can be detrimental to aquatic life and human health. The water quality monitoring conducted for this project has highlighted persistent issues in a number of Saint John area watersheds which would benefit from restoration or remediation activities.

5.2 Sediment PAHs

Most sites (seven of 13) in the Saint John Harbour had sediment PAH concentrations within an acceptable range comparable to local literature (Van Geest et al. 2015, Zitko 1999). The six sites with mean concentrations above the disposal-at-sea limit (2.5 mg/kg) were Digby Ferry Terminal, Courtenay Bay, Little River, Spar Cove, Tin Can Beach, and Marsh Creek. All these sites are in close proximity to industry or other commercial activities, and/or have historically been used for industrial purposes. The persistence of these contaminants in the sediments around Saint John is concerning for aquatic health, though the PAHs present in the greatest abundances may be unlikely to readily enter food webs and compromise the health of some aquatic organisms.

Sediment PAHs were extremely high in Marsh Creek, likely due to historical creosote contamination. Creosote in the downstream section of Marsh Creek may enter the Saint John Harbour through the Courtenay Bay Causeway; this can introduce PAHs and a number of other contaminants into the Harbour. Managers may explore the possibility of a Marsh Creek restoration project targeting the creosote contamination, which would improve conditions for aquatic life within the watercourse as well as humans.

5.3 Biotic Communities

A total of 35,213 fish and invertebrates were caught in beach seines and fyke nets between 2018 and 2021. Atlantic silverside and sand shrimp were the most abundant species, though the majority of Atlantic silverside were caught at Spar Cove. As a result of these high silverside numbers, Spar Cove had the lowest species diversity of all monitored sites in this study. The greatest species diversity was measured at Little River, Inner Harbour, Marsh Creek, and Tin Can Beach. Little River and Marsh Creek contained more freshwater species that were not observed in coastal sites. As described above, these two watercourses have the poorest water quality measured in this study. While Little River is home to a variety of species, it had the lowest abundance by far (328 individuals) and captured fish often appeared unhealthy or injured. Little River and Marsh Creek may be important habitats for aquatic organisms, especially since juvenile fish were often observed in Marsh Creek. Increasing temperatures may exacerbate the issues associated with contamination and further degrade these habitats until they can no longer support a diversity of aquatic life. These locations should be targeted for not only continued monitoring but also more active management and restoration.

The Saint John Harbour and surrounding watersheds contain considerable species diversity. The species sampled in this study exhibited temporal and spatial trends in abundance and size. An increase in juvenile Atlantic tomcod in the summer months of 2021 is particularly noteworthy. Documenting patterns such as these contributes to the development of a comprehensive baseline that incorporates changes over time and space. Given the range of conditions represented in this report, it remains unclear whether common species such as Atlantic silverside and sand shrimp could be used as sentinels of environmental change. It appears that Little River is inhospitable to organism health to some extent, given the low abundances observed there, and conditions within Marsh Creek may pose a threat to the organisms within the watercourse. The water quality issues identified in other monitoring sites, such as Kennebecasis Drive, could prompt further studies of aquatic health to identify whether freshwater fish and invertebrate habitat is compromised.

The lengths and abundances of fish and invertebrates were not directly related to water quality parameters in this report because water quality monitoring was not conducted concurrently with biotic community sampling. Future analyses can include developing a more robust correlation framework between abiotic variables and biotic data in order to evaluate potential abiotic drivers of biotic patterns. Researchers and managers can use the data in this report to inform the development of future studies and management plans. Strengthening and expanding the baseline data presented in this report will further benefit future research and promote the development of effective management plans for the Saint John region.

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Appendix – Supplementary Materials

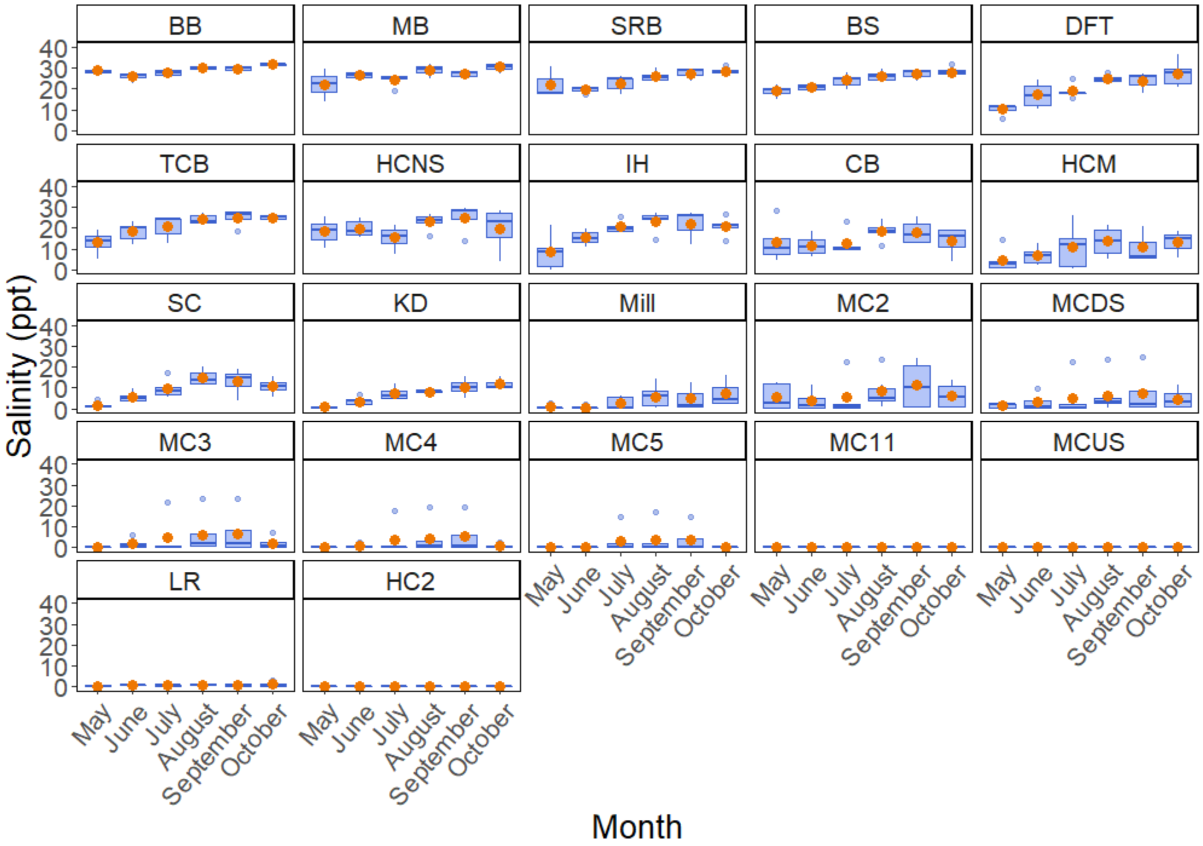
Supplementary Table 1. Temperature (°C), dissolved oxygen (mg/L), pH, conductivity (µS/cm), salinity (ppt), turbidity (NTU), ammonia, orthophosphate, phosphorous (mg/L), and *E. coli* concentration (MPN/100 mL) of 22 sites in and around the Saint John Harbour. Values are reported as the mean and standard deviation (SD) of *in-situ* measures from YSI and turbidity meter readings and laboratory analyses (2018 – 2021).

Site	**Temperature (°C)**		**Dissolved Oxygen (mg/L)**		**pH**	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
Black Beach	12.35	2.93	9.47	1.30	7.92	0.40
Bayshore	13.81	3.47	9.28	1.48	7.99	0.26
Courtenay Bay	14.55	3.77	8.94	1.52	7.60	0.35
Digby Ferry Terminal	14.16	3.36	9.80	1.70	7.99	0.33
Hazen Creek 2/Expansion	12.16	3.45	10.56	2.05	7.85	0.50
Hazen Creek Mouth	15.54	4.70	9.33	1.95	7.81	0.33
Hazen Creek Nearshore	14.51	3.43	9.46	1.48	7.90	0.30
Inner Harbour	13.45	2.38	9.48	1.69	7.88	0.25
Kennebecasis Drive	17.77	5.04	8.67	2.57	8.01	0.49
Little River	19.60	4.87	8.33	2.35	8.06	0.44
Mispec Beach	12.10	2.83	9.36	1.69	7.79	0.36
Marsh Creek 11	15.26	4.21	8.01	1.93	7.66	0.42
Marsh Creek 2	15.54	3.92	8.04	1.77	7.67	0.31
Marsh Creek 3	16.00	4.23	8.06	1.70	7.68	0.31
Marsh Creek 4	15.83	4.09	7.74	1.74	7.65	0.42
Marsh Creek 5	15.67	4.10	7.43	1.78	7.70	0.40
Marsh Creek Downstream	15.70	3.95	7.71	1.51	7.66	0.32
Marsh Creek Upstream	14.01	4.07	9.53	1.72	7.71	0.41
Mill Creek	17.09	4.29	8.72	1.89	7.99	0.42
Spar Cove	15.98	3.74	8.73	1.43	7.89	0.32
Saints Rest Beach	13.74	3.75	9.52	1.54	8.02	0.32
Tin Can Beach	13.31	2.59	9.59	1.69	7.86	0.30

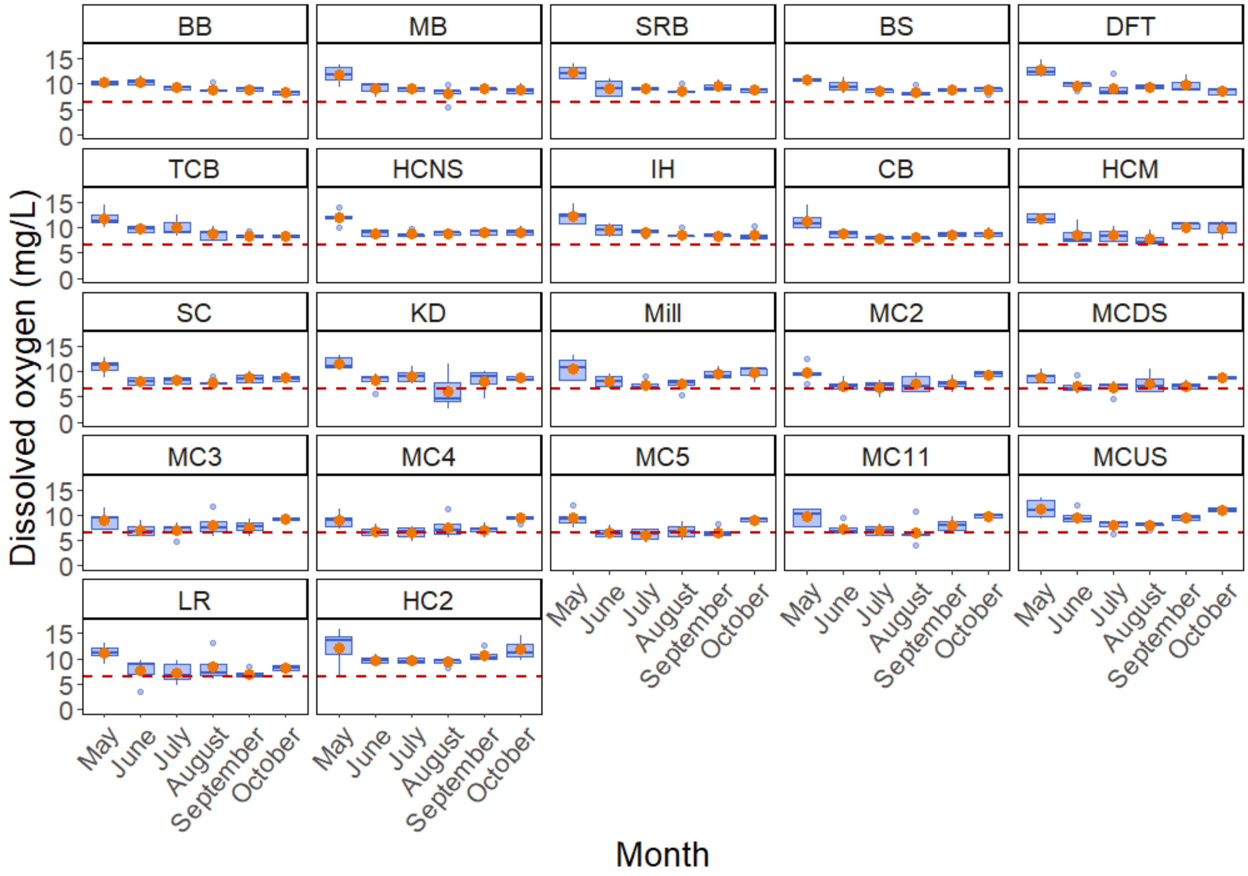
Site	**Conductivity (µS/cm)**		**Salinity (ppt)**		**Turbidity (NTU)**	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
Black Beach	45224	8842	30.04	5.92	30.49	36.99
Bayshore	37970	8123	24.89	5.36	28.48	32.09
Courtenay Bay	23789	9894	14.71	6.42	13.79	10.79
Digby Ferry Terminal	32852	10479	20.87	7.00	47.35	72.64
Hazen Creek 2/Expansion	290	280	0.19	0.26	4.48	10.40
Hazen Creek Mouth	15032	11129	9.56	7.38	13.40	19.87
Hazen Creek Nearshore	29854	11784	20.90	6.09	93.28	134.69
Inner Harbour	29586	9437	18.74	6.52	9.35	9.31
Kennebecasis Drive	11098	7103	6.44	4.31	7.28	13.28
Little River	1289	1089	0.71	0.60	14.49	26.45
Mispec Beach	37075	11973	26.63	4.19	22.20	24.72
Marsh Creek 11	361	117	0.17	0.052	9.64	12.94
Marsh Creek 2	11672	12780	6.79	7.82	9.25	8.56
Marsh Creek 3	6324	11185	3.77	7.07	9.22	7.43
Marsh Creek 4	4370	9259	2.60	5.77	10.50	8.43
Marsh Creek 5	3752	7911	2.12	4.79	8.17	8.31
Marsh Creek Downstream	8410	11461	4.70	7.19	9.83	8.41
Marsh Creek Upstream	200	166	0.081	0.032	7.08	13.57
Mill Creek	6329	7830	3.67	4.72	3.14	5.61
Spar Cove	15700	10339	9.07	5.92	9.62	20.02
Saints Rest Beach	38745	8705	24.91	5.71	37.64	50.36
Tin Can Beach	31508	11217	21.62	4.87	37.88	38.63

Site	**Ammonia (mg/L)**		**Orthophosphate (mg/L)**		**P (mg/L)**	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
Black Beach	0.034	0.059	0.079	0.043	0.026	0.015
Bayshore	0.024	0.039	0.069	0.048	0.022	0.018
Courtenay Bay	0.082	0.049	0.11	0.042	0.036	0.013
Digby Ferry Terminal	0.055	0.082	0.083	0.059	0.024	0.019
Hazen Creek 2/Expansion	0.037	0.024	0.056	0.034	0.018	0.012
Hazen Creek Mouth	0.085	0.056	0.063	0.049	0.016	0.012
Hazen Creek Nearshore	0.082	0.086	0.098	0.065	0.035	0.026
Inner Harbour	0.026	0.026	0.073	0.050	0.018	0.013
Kennebecasis Drive	0.031	0.029	0.047	0.053	0.0094	0.014
Little River	0.61	0.24	0.78	0.66	0.31	0.25
Mispec Beach	0.019	0.024	0.083	0.044	0.033	0.012
Marsh Creek 11	0.10	0.10	0.093	0.16	0.013	0.015
Marsh Creek 2	0.13	0.056	0.072	0.034	0.026	0.012
Marsh Creek 3	0.11	0.063	0.074	0.043	0.028	0.017
Marsh Creek 4	0.11	0.069	0.076	0.056	0.023	0.023
Marsh Creek 5	0.10	0.057	0.080	0.056	0.029	0.019
Marsh Creek Downstream	0.12	0.059	0.086	0.043	0.031	0.015
Marsh Creek Upstream	0.068	0.053	0.062	0.046	0.015	0.012
Mill Creek	0.027	0.025	0.041	0.031	0.014	0.013
Spar Cove	0.041	0.031	0.070	0.043	0.018	0.013
Saints Rest Beach	0.047	0.069	0.10	0.066	0.027	0.019
Tin Can Beach	0.054	0.061	0.026	0.015	0.031	0.024

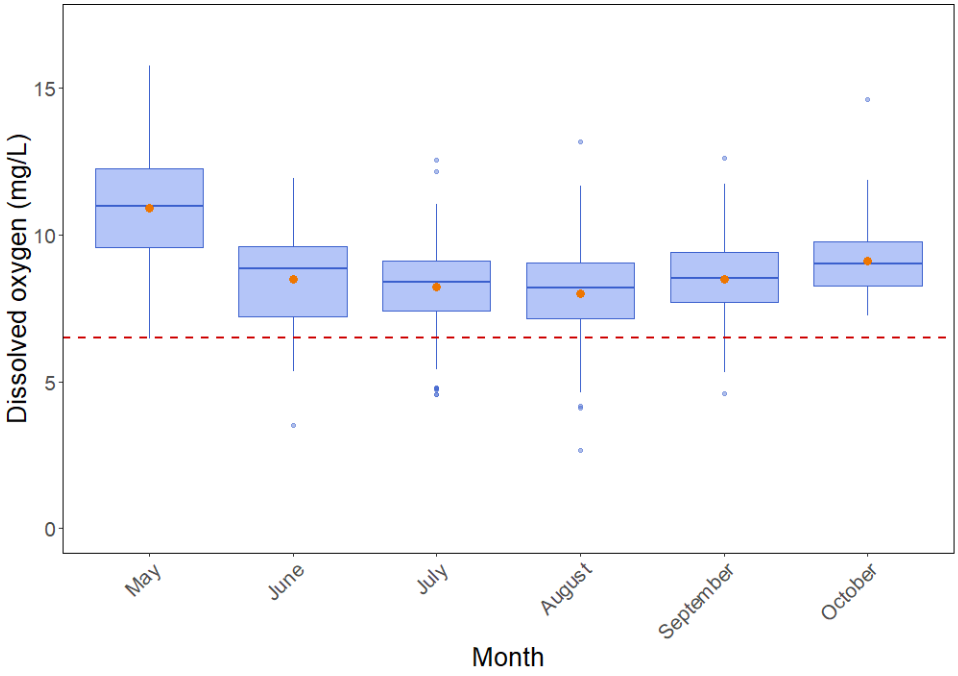
Site	***E. coli* (MPN/100 mL)**		
	Median	*Mean*	*SD*
Black Beach	10	128	479
Bayshore	10	26	31
Courtenay Bay	1500	1495	900
Digby Ferry Terminal	31	59	81
Hazen Creek 2/Expansion	19	151	474
Hazen Creek Mouth	160	390	612
Hazen Creek Nearshore	199	351	563
Inner Harbour	20	185	584
Kennebecasis Drive	53	427	763
Little River	54	234	577
Mispec Beach	10	56	117
Marsh Creek 11	657	870	722
Marsh Creek 2	2420	2271	379
Marsh Creek 3	1046	1352	825
Marsh Creek 4	770	1172	845
Marsh Creek 5	866	1164	824
Marsh Creek Downstream	2420	2181	472
Marsh Creek Upstream	345	966	938
Mill Creek	24	150	400
Spar Cove	1782	1667	820
Saints Rest Beach	10	33	79
Tin Can Beach	63	233	571



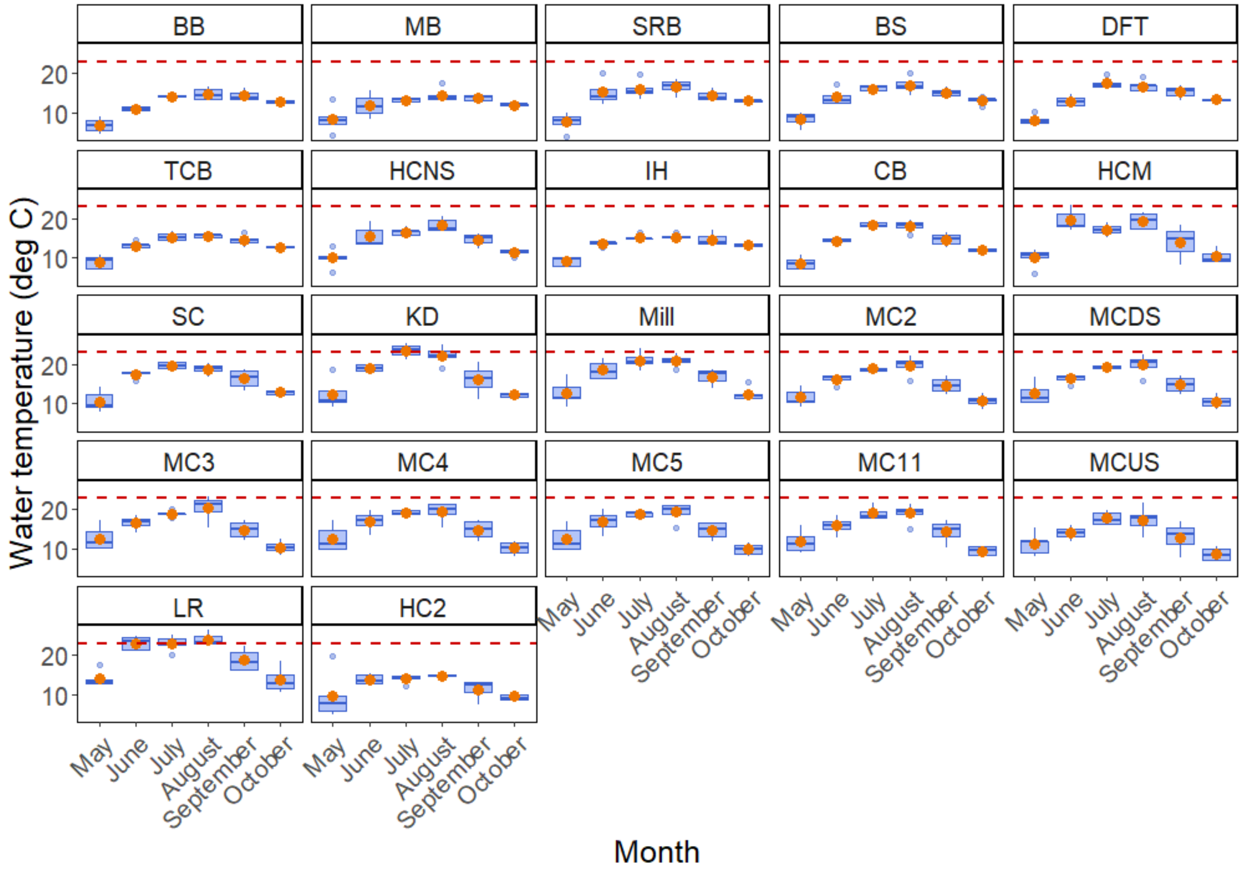
Supplementary Figure 1. Salinity (ppt) of each site across months (May – October) for all years (2018 – 2021).



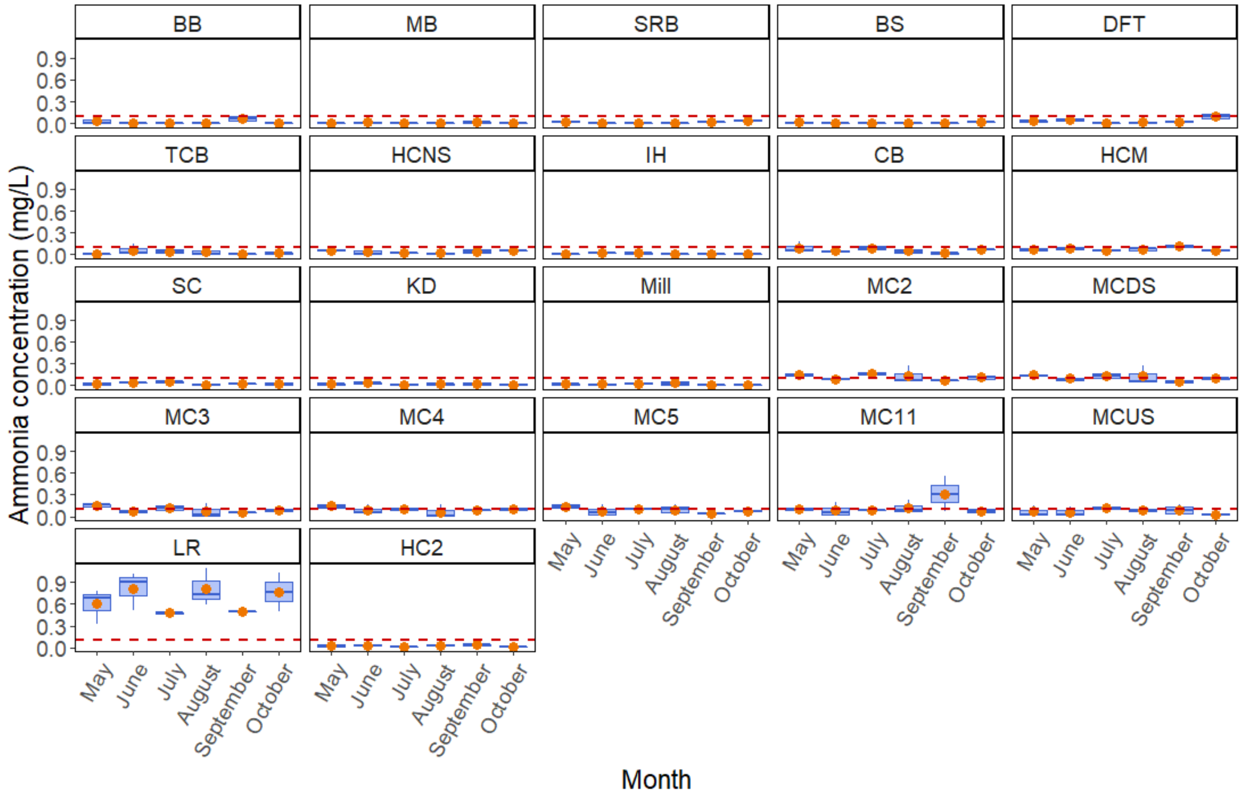
Supplementary Figure 2. Dissolved oxygen (mg/L) of each site across months (May – October) for all years (2018 – 2021).



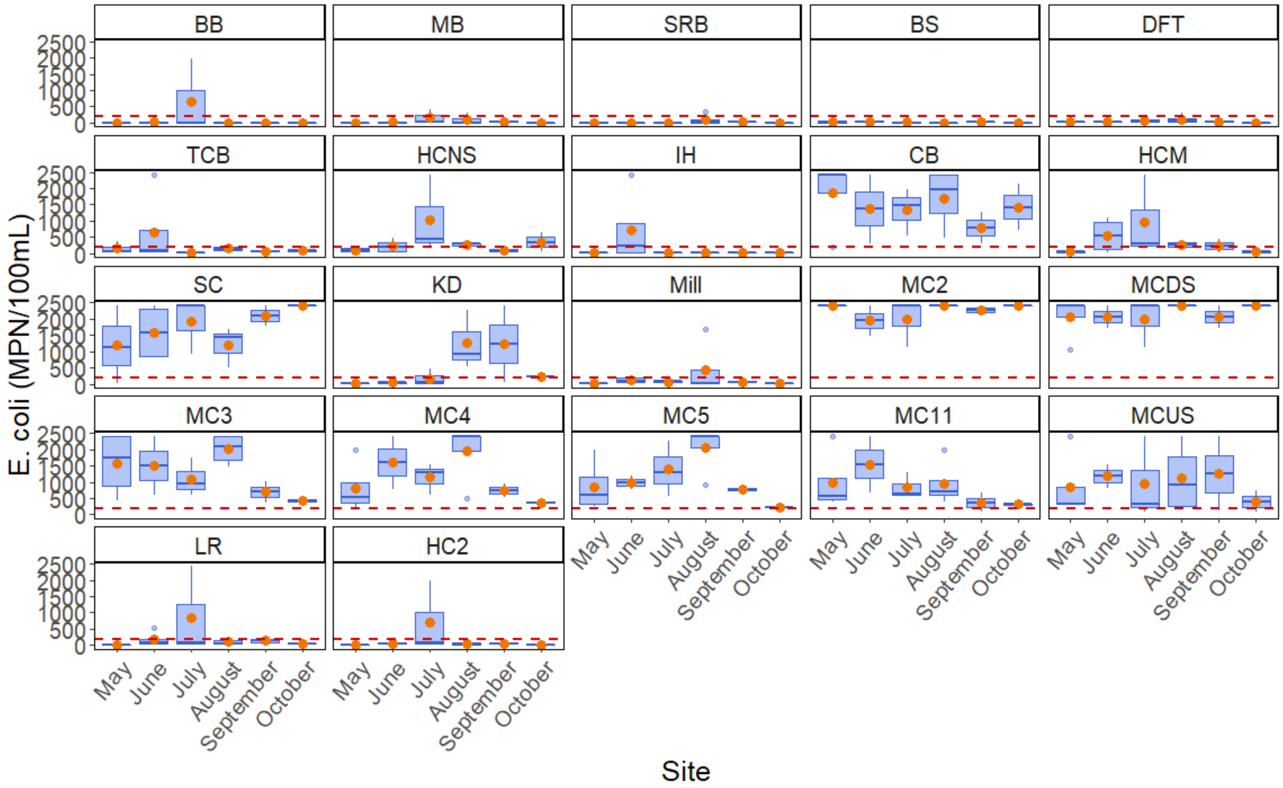
Supplementary Figure 3. Dissolved oxygen (mg/L) across all sites and months (May – October).



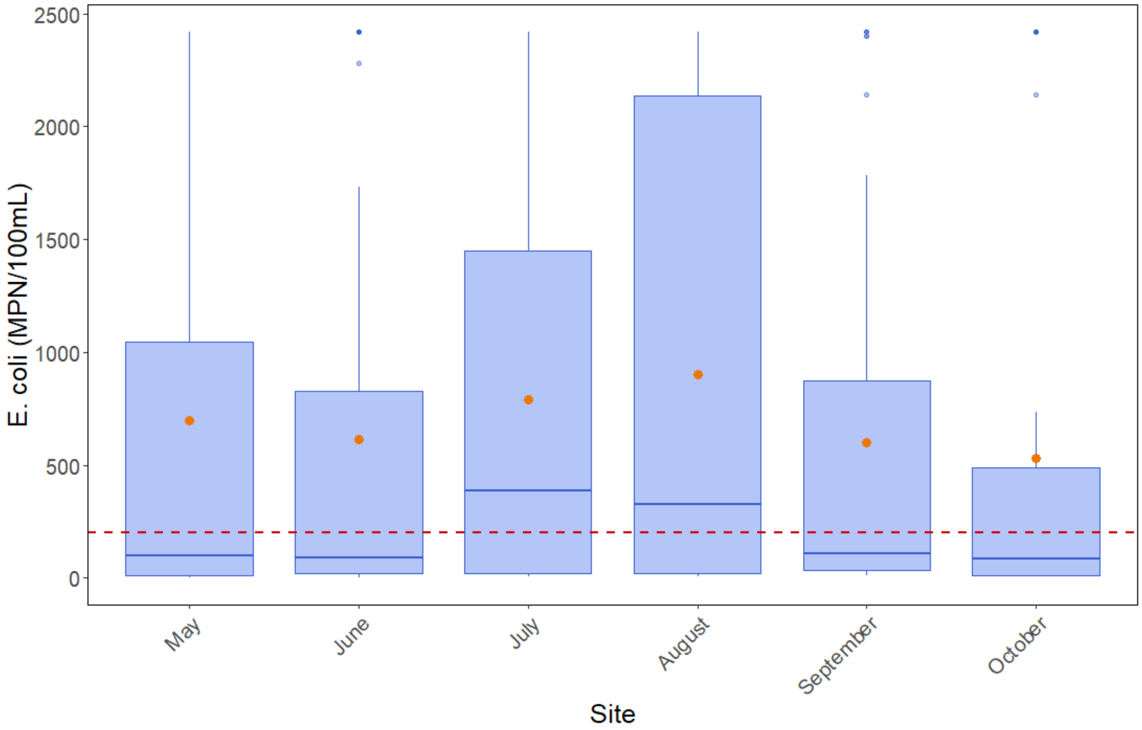
Supplementary Figure 4. Water temperature (°C) of each site across months (May – October) for all years.



Supplementary Figure 5. Ammonia concentrations (mg/L) of each site across months (May – October) for all years (2018 – 2021).



Supplementary Figure 6. *E. coli* (MPN/100 mL) of each site across all months (May – October) for all years (2018 – 2021).



Supplementary Figure 7. *E. coli* (MPN/100 mL) across all sites and months (May – October).

Supplementary Table 2. Mean ± SD for all sediment PAHs at 13 sites (2018 – 2022). All PAH concentration units are in mg/kg.

Site	**Acenaphthene**		**Acenaphthylene**		**Anthracene**		**Benz[a]anthracene**		**Benzo(g,h,i)perylene**		**Benzo[a]pyrene**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BS	0.006	0.002	0.006	0.002	0.006	0.002	0.007	0.002	0.006	0.002	0.006	0.002
BB	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002
CB	0.042	0.004	0.008	0.004	0.253	0.299	0.268	0.223	0.095	0.062	0.196	0.143
DFT	0.080	0.147	0.020	0.031	0.201	0.345	0.308	0.527	0.093	0.106	0.224	0.318
HCM	0.010	0.013	0.006	0.002	0.015	0.033	0.018	0.036	0.010	0.013	0.016	0.030
HCNS	0.006	0.002	0.006	0.002	0.007	0.004	0.009	0.006	0.006	0.002	0.008	0.005
IH	0.014	0.017	0.011	0.011	0.050	0.073	0.126	0.181	0.058	0.062	0.121	0.161
LR	0.053	0.109	0.045	0.075	0.175	0.199	0.287	0.360	0.199	0.165	0.288	0.325
MCDS	0.423	0.659	0.145	0.117	2.010	2.41	3.262	4.574	1.032	0.981	2.358	2.649
MB	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002
SRB	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002
SC	0.057	0.052	0.048	0.056	0.323	0.486	0.826	1.260	0.256	0.222	0.574	0.536
TCB	0.108	0.285	0.065	0.054	0.265	0.531	0.550	0.753	0.296	0.398	0.555	0.679

Site	**Benzo[b,j]fluoranthene**		**Benzo[e]pyrene**		**Benzo[k]fluoranthene**		**Chrysene + Triphenylene**		**Dibenz[a,h]anthracene**		**Fluoranthene**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BS	0.007	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.008	0.006
BB	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002
CB	0.283	0.216	0.144	0.103	0.101	0.072	0.252	0.188	0.026	0.018	0.610	0.543
DFT	0.291	0.448	0.140	0.212	0.112	0.177	0.264	0.475	0.028	0.035	0.705	1.269
HCM	0.019	0.033	0.012	0.016	0.010	0.013	0.018	0.030	0.006	0.002	0.030	0.070
HCNS	0.010	0.009	0.006	0.002	0.006	0.002	0.009	0.006	0.006	0.002	0.017	0.020
IH	0.152	0.204	0.076	0.099	0.056	0.078	0.103	0.154	0.015	0.018	0.246	0.365
LR	0.332	0.402	0.292	0.227	0.113	0.147	0.273	0.283	0.060	0.055	0.639	0.883
MCDS	2.998	3.069	1.498	1.634	1.161	1.312	2.802	3.704	0.318	0.349	9.022	15.918
MB	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002
SRB	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002
SC	0.708	0.683	0.366	0.353	0.295	0.332	0.688	1.111	0.068	0.056	3.029	7.529
TCB	0.661	0.784	0.319	0.366	0.242	0.306	0.460	0.620	0.079	0.109	1.185	1.853

Site	**Fluorene**		**Indeno[1,2,3-cd]pyrene**		**Naphthalene**		**Phenanthrene**		**Pyrene**		**Total**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BS	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.007	0.004	0.104	0.033
BB	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.099	0.032
CB	0.108	0.121	0.099	0.066	0.027	0.027	0.439	0.395	0.430	0.373	3.381	2.712
DFT	0.117	0.218	0.107	0.130	0.119	0.268	0.705	1.326	0.579	1.030	4.094	7.032
HCM	0.010	0.016	0.010	0.013	0.008	0.007	0.028	0.076	0.030	0.064	0.255	0.460
HCNS	0.007	0.004	0.006	0.002	0.007	0.004	0.015	0.021	0.015	0.015	0.144	0.095
IH	0.019	0.027	0.063	0.075	0.013	0.013	0.167	0.260	0.213	0.305	1.504	2.065
LR	0.050	0.081	0.162	0.183	0.025	0.025	0.484	0.697	0.675	0.733	4.151	4.497
MCDS	0.776	1.017	1.257	1.336	0.418	0.992	4.739	7.015	6.451	10.230	40.668	52.393
MB	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.099	0.033
SRB	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.006	0.002	0.098	0.032
SC	0.137	0.229	0.305	0.274	0.037	0.036	1.323	2.389	2.386	5.573	11.426	20.250
TCB	0.132	0.281	0.334	0.442	0.108	0.143	0.947	1.850	1.053	1.645	7.359	11.051

Supplementary Table 2. Total lengths (mean, SD, n) and total abundances (2018 – 2021) of all fish and invertebrates caught in fyke nets throughout the study period.

Common Name	**Scientific Name**	**Total Length**			**Total Abundance Across all Sites**				
		Mean	**SD**	**n**	**2018**	**2019**	**2020**	**2021**	**Total**
Atlantic Tomcod	*Microgadus tomcod*	173.2	35.1	833	141	387	175	221	924
White Sucker	*Catostomus commersonii*	115.6	38.4	95		8	86	67	161
Sand Shrimp	*Crangon septemspinosa*	14.8	7.7	74		33	25	16	74
Rainbow Smelt	*Osmerus mordax*	151.9	27.8	62		31	20	18	69
American Eel	*Anguilla rostrata*	441.3	150.0	36	14	12	6	7	39
Winter Flounder	*Pseudopleuronectes americanus*	141.3	84.1	56		17	7	37	61
Golden Shiner	*Notemigonus crysoleucas*	98.6	17.1	20		2	18		20
Threespine Stickleback	*Gasterosteus aculeatus*	55.6	10.7	18		8	9	2	19
***Alosa* sp.**	*Alosa sp.*	90.4	32.1	14	2	5	5	4	16
Pollock	*Pollachius virens*	155.0	26.9	11	1	7	3		11
Hake	*Urophycis sp.*	133.9	31.3	9		8		1	9
Mummichog	*Fundulus heteroclitus*	90.9	10.9	12	1	6	1	7	15
Atlantic Rock Crab	*Cancer irroratus*	843	14.9	4	2	1	2	12	17
White Perch	*Morone americana*	146.3	42.0	3	1	2			3
Blueback Herring	*Alosa aestivalis*	80.0		1				1	1
***Cancer* sp.**	*Cancer sp.*					1			1
Central Mudminnow	*Umbra limi*	83.0		1				1	1
Common Shiner	*Luxilus cornutus*	49.0		1			1		1
Jonah Crab	*Cancer borealis*					1			1
Lake Chub	*Couesius plumbeus*	110.0		1			1		1
Longhorn Sculpin	*Myoxocephalus octodecemspinosus*	335.0		1			1		1
Northern Crayfish	*Orconectes virilis*	40.0		1		1			1
Total					162	530	360	394	1447

Supplementary Table 3. Total lengths (mean, SD, n) and total abundances (2018 – 2021) of all fish and invertebrates caught in seine nets throughout the study period.

Common Name	**Scientific Name**	**Total Length**			**Total Abundance Across all Sites**				
		Mean	**SD**	**n**	**2018**	**2019**	**2020**	**2021**	**Total**
Atlantic Silverside	*Menidia menidia*	78.6	15.3	1111	1460	7366	4354	1460	14640
Sand Shrimp	*Crangon septemspinosa*	7.8	6.5	2691	842	5010	3059	5239	14150
Threespine Stickleback	*Gasterosteus aculeatus*	39.9	20.0	538	30	1928	148	203	2309
Banded Killifish	*Fundulus diaphanus*	35.9	11.7	90	1	591	4	1	597
Rainbow Smelt	*Osmerus mordax*	68.9	23.1	180	39	106	29	32	206
Blackspotted Stickleback	*Gasterosteus wheatlandi*	33.5	7.4	125	2	110	41	17	170
Winter Flounder	*Pseudopleuronectes americanus*	71.0	54.0	184	12	81	58	33	184
Mysid	*Mysidae*	7.3	4.3	73	1	32	90	2	125
Mummichog	*Fundulus heteroclitus*	53.5	7.5	60	4	24	69		97
Ninespine Stickleback	*Pungitius pungitius*	47.7	6.5	44	65	3		5	73
Atlantic Tomcod	*Microgadus tomcod*	78.6	29.9	268	4	34	22	1061	1121
Fourspine Stickleback	*Apeltes quadracus*	36.5	9.7	23	9	7	3	4	23
Alosa sp.	*Alosa sp.*	51.3	2.2	14		14			14
Hake	*Urophycis sp.*	65.5	11.4	15	1	2	10	2	15
Pollock	*Pollachius virens*	42.3	5.5	6		6			6
***Gasterosteus* sp.**	*Gasterosteus sp.*	24.8	6.8	10				11	11
Northern Pipefish	*Syngnathus fuscus*	119.8	39.3	8	1	2	1	4	8
Blueback Herring	*Alosa aestivalis*	50.5	7.8	2				2	2
Lake Chub	*Couesius plumbeus*	5.5	0.7	2		2			2
American Eel	*Anguilla rostrata*	156.7		1				1	1
***Peprilus* sp.**	*Peprilus sp.*	37.0		1				1	1
Grubby	*Myoxocephalus aenaeus*	26.0		1		1			1
Haddock	*Melanogrammus aeglefinus*	33.0		1		1		1	2
Rock Gunnel	*Pholis gunnellus*	89.5	0.7	2			1	1	2
Shorthorn Sculpin	*Myoxocephalus scorpius*	109.0		1		1			1
Smooth Flounder	*Pleuronectes putnami*	58.0		1			1		1
White Sucker	*Catostomus commersoni*	83.0	18.0	4			1	3	4
Total					2471	15321	7891	8083	33768