

Ship Wake Influence on Fish Communities in the Upper St. Lawrence River

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Abstract

The St. Lawrence River is home to large vessels that travel between the Atlantic Ocean and the Great Lakes. Ships that travel throughout the waterway generate both primary and secondary waves that travel towards the nearshore ecosystem, disrupting the fish communities. With the increase in novelty of ship hydrodynamics and ecology, this is the first study that incorporates both disciplines into one. The Upper St. Lawrence River is an ideal river for surveying as it spans over 240 kilometres long and up to 7 kilometres wide. The Fish Identification Nearshore (FINS) research team at the St. Lawrence River Institute surveyed over 230 sample locations to perform more than 600 fish surveys. In their database, they contain data for fish surveying through abundance (the total fish count) and richness (total fish species) at each site location, environmental DNA (eDNA) sampling, water quality measurements, habitat and vegetation sampling, and drone imaging. This research uses the FINS database to find correlations between the ships that travel throughout the Upper St. Lawrence River and the data within the database. The primary analysis of this research is to find correlations based on direct exposure to the shipping lane and the distance to the shipping lane from the designated site locations. Secondary analyses consist of exposed site locations within 1 kilometre of the shipping lane for: (1) the coastline geometry classified as straight shoreline or embayment shoreline, and (2) the dominant substrate, and (3) the habitat type classified as wetland or non-wetlands. Four different statistical analyses were used depending on the distribution of fish abundance and fish richness: (1) regression slope analysis for R^2 correlations, (2) analysis of variance (ANOVA) for normal distributions, and non-parametric methods for skewed distributions of (3) Mann-Whitney U testing for categories with two independent groups, and (4) Kruskal-Wallis H testing for categories with more than two independent groups. Probability values where the value was less than 0.05 demonstrated statistically significant results. Effect sizes accompanied the probability values. Results demonstrated the following outcomes: (1) a negative correlation between fish richness and proximity of ships towards the shoreline, (2) higher fish richness at exposed embayment site locations compared to straight shorelines, (3) higher fish richness with site locations primarily consisting of finer grain sizes (sand and clay) and lower fish richness with site locations with site locations consisting of coarser grain sizes (cobble and gravel), and (4) habitat type did not deliver statistically significant results. In summary, sites close to the shipping lane with rocky straight

shorelines were found to have reduced fish community abundance and diversity, presumably due to the influence of nearshore wave action.

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List of Symbols

ANOVA	Analysis of variance
F_h	Depth Froude number
η^2	Effect size
eDNA	Environmental DNA
FINS	Fish Identification Nearshore
p-value	Probability value
v	Velocity (m/s)

1 Introduction

The St. Lawrence River is a navigational waterway recreational and commercial scale. Ships as large as 225.5 metres long and 23.8 metres wide travel throughout the St. Lawrence River. The seaway system that connects the St. Lawrence River and the Great Lakes is a vital waterway that provides the third largest economic value in the world based on gross domestic product (Seaway 2026). However, navigation vessels in waterways cause harsh effects on the morphology of rivers and nearshore ecosystems (Gabel et al. 2017). In particular, the hydrodynamics from both ship generated waves and currents exert significant energy towards natural environmental shorelines which erodes the bed and banks (Dempwolff et al. 2022). As a result, the House of Commons Standing Committee on Transport, Infrastructure and Communities held two meetings to discuss the impact of shipping on shoreline erosion where reputable and knowledgeable stakeholders brought forward concerns and solutions to shoreline erosion caused by shipping (Schiefke 2023). In addition, fish communities are sensitive to environmental disturbances. In particular, wave exposure impacting swimming performance and habitat selection (Depczynski and Bellwood 2005; Friedlander et al. 2003; Kucera-Hirzinger et al. 2009), sediment resuspension impacting foraging (Gregory and Northcote 1993; Utne-Palm 2004), and anthropogenic noise impacting fish behaviour and physiology (Cox et al. 2016).

Furthermore, studies focusing on ship generated waves are increasing, primarily towards hydrodynamics and shoreline erosion. Conversely, the paucity of ecological effects from ship-generated waves is apparent. Huckstorf et al. (2011) demonstrated that width-restricted waterways impoverish fish communities due to the negative hydraulic disturbances along the shoreline. Additionally, (Gutreuter et al. 2006) found a negative correlation between fish abundance and species density in navigational waterways compared to larger calmer waters. While these two research papers provide empirical evidence, further research provides additional insight to the problems against the nearshore ecosystem.

As a result, this thesis provides additional insight towards the ship wake influence on the nearshore ecosystem. Similar research in the Upper St. Lawrence River, focused in the Thousand Islands by Henning et al. (2014) provides insight into fish communities. This research demonstrated that unique fish species prefer either exposed or protected shoreline habitats depending on their size, their wave-exposure tolerance, and their desire to be in highly dense

vegetation sites. Despite their research providing strong evidence, it fails to involve the influence from ship-generated waves. This thesis embodies qualities from Henning et al. (2014) through exposure to waves, habitat types, and dominant substrates; however, in addition, it provides ship-generated waves with the distance to the shipping lane and exposed shoreline geometries towards over 230 site locations and over 600 fish surveys compared to the eight from Henning et al. (2014). To provide empirical evidence, this thesis uses the Fish Identification Nearshore (FINS) database provided by the St. Lawrence River Institute and the Mohawk Council of Akwesasne, demonstrating the influence of ship wake waves towards fish abundance and fish richness in the Upper St. Lawrence River.

1.1 Organisation of Thesis

The thesis is comprised of an original research article found in Chapter 2. The article will be submitted to a peer-reviewed journal. The article presents a brief overview on relevant literature pertaining to the study of ship wakes, ship wake influence on fish communities, wave impact on fish communities and their surrounding habitats, and research conducted throughout the St. Lawrence River.

Chapter 1 presents the introduction, thesis organisation, novelty of the study and provides the research objectives and project contributors.

Chapter 2 presents the article titled Ship wake influence on nearshore fish community structure in the Upper St. Lawrence River and is under review at the time of this writing. Field data collected by the Fish Identification Nearshore (FINS) team at the St. Lawrence River Institute provides a unique database of over 600 collected fish surveying samples across over 230 site locations within the Upper St. Lawrence River. This database includes fish surveys, environmental DNA collection, water quality measurements, vegetation sampling, and drone imagery. A shipping lane in ArcGIS was drawn using buoy locations from nautical charts. Distances between the shipping lane and the individual site locations were calculated. Binary classification between exposed and protected (e.g., sheltered by islands) towards the shipping lane was used. Statistical analyses were performed using IBM SPSS statistics software. In addition to regression slope analysis for R^2 correlations, three different statistical methods were used to determine statistically significant difference ($p < 0.05$) between the means of the independent groups in relation to the

dependent variables (fish abundance or fish richness). For normal distributions, an analysis of variance (ANOVA) method was used. For skewed distributions, a non-parametric method was used depending on the number of groups within the independent variable. Mann-Whitney U was used for two categories, meanwhile Kruskal-Wallis H was used for any variable with more than two categories. Accompanied with the p-values, an effect size values, η^2 , to demonstrate the magnitude. Distributions of fish richness were illustrated using box-and-whisker plots.

Chapter 3 presents the overall conclusions of the thesis, discusses the limitations, and provides recommendations for future work.

1.2 Literature Review

1.2.1 Ship Wakes

Waterways are commonly used for navigation at a recreational and commercial scale. Ships navigating through waterways generate waves that propagate towards the shoreline. These waves are called ship wake. Ship wake comprises of two components – primary waves known as drawdown waves, and secondary waves known as Kelvin waves (Dempwolff et al. 2022).

The primary component to ship wake are drawdown waves. Ships traveling push water to the side and underneath which leaves an open space behind for water to fill in. This causes the water to accelerate, increasing the velocity and the kinetic energy, while decreasing the pressure and potential energy. As a result, the water level in the flow field drops (Bhowmik et al. 1981) and an increase in local elevation at the stern and bow of the ship, generating waves from the variation in water level (Dempwolff et al. 2022). Characteristics of drawdown waves are functions of multiple factors. The wavelength and the number of waves in a wake train corresponds with the length of the ship (Gharbi et al. 2010) while the wave height is a function of the ship's cross section and speed (Bhowmik et al. 1981). Figure 1 illustrates the water surface elevation change (black line) with respect to the still water level (blue line) for a ship travelling at a velocity, v , and the depth Froude-number, F_h .

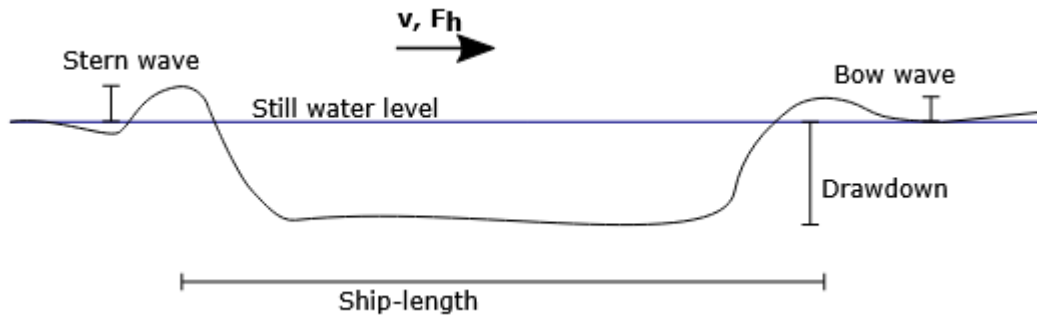


Figure 1. Sketch of drawdown wave travelling in the direction of the velocity arrow. The black line generates the surface of the water caused by the ship with the blue line acting as a still water reference level (Dempwolff et al. 2022).

The secondary component to ship wake are commonly known as Kelvin waves. Two patterns are generated from Kelvin waves: transverse (perpendicular with the ships movement) waves and divergent (parallel with the ships movement) waves. These two wave patterns intersect at the cusp-

line, usually at an angle of 19.5° (Dempwolff et al. 2022; Yang et al. 2011) illustrating a V-shape from a birds eye view.

Ship wake research most commonly revolves around sediment transport. In 2014, Göransson et al. (2014) observed sediment transport, bed erosion, and bank erosion due to ship navigation in the Göta Älv River in Sweden. They observed maximum turbidity as a positive function of drawdown height and a negative function of water depth with direction of shipping influencing the magnitude on turbidity measurements. A year later, Rapaglia et al. (2015) observed that drawdown waves from commercial ships lead to large-scale sediment resuspension in the Venice Lagoon, Italy. They found that the largest effects occurred when large ships travelled at high speeds during low tide periods. Additionally, they found that coarse grained sediments moved towards the shipping lane when high levels of suspended sediment concentrations were pulled in from drawdown waves. In 2025, Haghighi et al. (2025) observed in the Upper St. Lawrence River that ship wake generated short intense turbidity spikes, particularly in shallow zones with fine sediment while wind waves regularly resuspended sediment. The exposed site locations in the St. Lawrence River observed higher wave amplitude compared to the protected site locations (Haghighi et al. 2025). Finally, Joubert and Figlus (2026) observed a strong correlation with the total magnitude of net sediment transport due to drawdown height, whereas a combination of maximum secondary wave height and drawdown height correlated with mean and maximum suspended sediment concentrations. They also observed that the total sediment transport for most ship wakes was found to be in the opposite direction of wake propagation. Sediment transport is the forefront of ship wake research and will continually be researched to find ways to minimize the adverse effects.

Another domain with respect to ship wake research is bank erosion. Early on, Nanson et al. (1994) found that the wave energy from 5-10 centimetre waves are strong enough to cause bank erosion. They observed that at maximum wave heights above 35 centimetres nearly every bank would erode. As a result, speed restrictions were implemented to reduce maximum wave heights to below 30 centimetres (Nanson et al. 1994). Later, Houser (2010) observed that roughly 25% of the total wave energy at their site in the Savannah River, USA resulted in shoreline erosion. Styles and Hartman (2019) observed vessel waves with respect to the tides. They found higher concentrations of suspended sediment from bank erosion when the bank was exposed (generally at low tide). They also noted that breaking vessel waves were the primary contributor to sediment transport along the

shoreline in areas where saltmarshes acted as protection from wind waves. Most recently, Duró et al. (2020) studied the effects of navigation on bank erosion. Their results demonstrated that the shear forces primary waves from ships altered the terrace, especially during low flows. Additionally, they observed that the magnitude of the primary waves controls the long-term terrace. However, they found that as the terrace dissipates waves more efficiently as it evolves.

Another explored element is the difference in hydrodynamics based on the characteristics of different vessels. Liedermann et al. (2014) observed three different types of ships: large passenger ships, high speed passenger ships, and bulk carriers. They found that large passenger ships and bulk carriers had similar patterns of a drawdown wave, meanwhile the high speed passenger ships produced oscillatory waves at a higher frequency and lowered wave heights. They observed a decrease in wave heights decreased as the proximity towards the ships increase. An increase of 50 metres from the shipping lane decreased the wave height by 8 centimetres for high speed passenger ships. Additionally, they observed that ship speed increased wave heights. A reduction in velocity by 5 km/h for passenger ships decreased the primary wave height by 14 cm. Additionally, Parnell et al. (2007) observed that long ship wake lengths from high speed boats up to seven kilometres from the shoreline and Shuster et al. (2020) observed that smaller recreational boats within 30 metres of the shoreline can be a useful predictor for wake energy.

Finally, there is a paucity in the research on ecological impacts from ship wakes. Most notably, Huckstorf et al. (2011) observed lower fish abundance in areas with higher ship traffic from the physical drawdown forces and return currents, especially along width-restricted waterways compared to low intensity areas. This concept was also observed by Gutreuter et al. (2006) who found a negative correlation of fish abundance and fish species in navigation channels relative to larger secondary channels. Additionally, another study has shown that swimming performance for fish cannot withstand the harsh conditions during ship passages (Kucera-Hirzinger et al. 2009). Finally, there are some studies that have shown fatal effects to fish ecology due to stranding (Adams et al. 1999) and dewatering (Holland 1987) from vessel wakes. These studies are the forefront of illustrating the effects of ship wakes on nearshore ecosystems.

Sediment transport in terms of turbidity levels and sediment resuspension is the forefront of ship wake research. Other domains such as bank erosion, wave hydrodynamics, and ecological impact are rising in research. Previous studies consistently demonstrate that ship wakes increase sediment

resuspension and shoreline erosion, although the governing mechanisms differ depending upon vessel type and channel geometry. The increase in studies can help improve knowledge gap which may result in a stronger and sustainable ecosystem.

1.2.2 Wave Impact on the Nearshore Fish Communities

Waves heavily influence the nearshore fish communities their surrounding environment. Waves are a strong source of energy that shapes the physical environment and regulates ecological processes. Researchers have been investigating wave impact across multiple different factors. Notably, habitat exposure to waves has a strong influence on fish abundance, diversity, and biomass. Additionally, waves generate turbulence which cause sediment to suspend, measured by turbidity levels. Finally, waves influence the swimming performance for fish.

One of the main wave impacts on the nearshore ecosystem stems from research of fish communities in wave-exposed habitats. Many studies have shown that protection from wave exposure is necessary to sustain the nearshore ecosystem. In 2003, Friedlander et al. (2003) found that most fish showed positive correlations to protection whether it was physical, biological, or human-induced. Higher fish biomass was observed in protected areas; conversely, lower fish biomass in exposed sites. Additionally, they observed higher fish biomass, diversity, and abundance in locations with higher substrate complexity which demonstrates that protection is only one factor in habitat selection for fish. More research has shown similar trends. Depczynski and Bellwood (2005) observed 44 different species in the Great Barrier Reef. They found three clear trends. The first showed higher abundance and richness in microhabitats composed of a mix of sand and rubble compared to the open reef microhabitats. 41 of the 44 species rested among the mix of sand and rubble microhabitats while 27 species were in the open reef samples. The second was that patterns of abundance, diversity and size/weight class distributions varied at exposed site locations, meanwhile protected site locations had little variation. The third was species compositions varied along exposed and protected reef sites. Exposure to waves decreased the abundance and richness. They believe small fish exhibited a negative correlation with swimming abilities in the exposed shorelines due to the waves. Finally, Henning et al. (2014) observed similar trends to Friedlander et al. (2003) and Depczynski and Bellwood (2005) where protected shorelines increased fish diversity, dominated by fish species that preferred large amounts of vegetation, meanwhile the exposed shorelines were preferred by fish species who prefer firmer

substrates. These previous research papers demonstrate wave exposure sites have negative correlations for fish abundance, diversity and biomass. Furthermore, Stoll and Beeck (2012) observed that fish as young as 1 week old can sense wave pulses and migrate to calmer waters to avoid wave exposure.

While protected and exposed locations illustrate correlations to fish abundance, diversity, and biomass, other factors are influenced by waves along the nearshore environment. One of the main impacts is the effect on fish performance. Two studies have shown the impact of sediment suspension through the magnitude of turbidity. Increased turbidity results in visibility challenges for foraging. Gregory and Northcote (1993) and Utne-Palm (2004) demonstrated that foraging rates were hindered during high levels of turbidity and low, clear water conditions for both surface or benthic level prey. In both studies, the highest rate of foraging was found during the intermediate turbidity levels. However, with one exception, the largest fish benefited from high levels of turbidity.

Another wave influence on the fish ecosystem is through fish swimming performance. Swimming performance is a crucial factor for fish survival. Swimming speed limits and endurance are important for capturing food, escaping from predators, and reproducing. Fish need to be able to swim faster than the maximum wave velocities in order to navigate through water (Wolter and Arlinghaus 2003). Haak et al. (2019) observed a negative correlation in fish abundance in due to high levels of hydrodynamic variables such as wave energy and flow rates. As a result, young fish would migrate to habitats with lower flowrates. Finally, Henning et al. (2014) observed that large fish who could withstand strong waves preferred exposed shorelines compared to smaller fish who could not withstand strong waves preferred substantial vegetation and calmer waters.

Wave activity is an important physical factor for nearshore fish communities. Negative correlations for fish abundance, richness, and biomass are seen for site locations exposed to waves. Similar finds towards waves that suspends sediment can hinder fish visibility. Finally, high wave energy impacts swimming performance and fish are forced to migrate to calmer areas where they are not overpowered by hydrodynamic forces.

1.2.3 St. Lawrence River Studies

The St. Lawrence River is commonly used for commercial and recreational ships. However, most studies conducted in the St. Lawrence River has not explored shipping influence. Most ecological research focuses on the health of fish by observing levels of metal, fish sampling and monitoring invasive species, and more recently, the impact of shipping.

The Upper St. Lawrence River is largely diverse and contains a variety of different aquatic species. In 2024, the Fish Identification Nearshore survey team found 47 different species of fish (Ehrenfeld et al. 2024). With the numerous aquatic wildlife, researchers develop ways to sample riparian zones through traditional methods such as seining and chemical methods such as environmental DNA testing (Maracle et al. 2024). At the same time, researchers develop ways to find concentration of contaminants, primarily through sediments. In the Upper St. Lawrence River, ecological research strives in the safety of the fish communities focusing on concentration levels of various metals, most notably mercury, but also zinc. Armstrong et al. (2021) observed strong ecological changes occurring simultaneous with human industrial activity. They found that remains of tiny aquatic insects (chironomids) in surface sediments. They found older sediments were able to tolerate high levels of zinc, meanwhile they found a negative correlation between chironomids and high concentrations of mercury. From 1980 onwards, lower mercury levels were found in sediment resulting in an increase in chironomids and believed this result was due to the mercury regulations. In the same year, Moir et al. (2021) found high levels of mercury in surface sediments and spatial distribution of contaminants was highly heterogeneous across their site locations from variable sedimentation and small resuspension patterns. In terms of fish, Osgood et al. (2022) observed higher mercury levels in fish collected in wetlands compared to the non-wetlands for both yellow perch and round gobies. With industrializing becoming more apparent in later years, Brahmstedt et al. (2026) researched the effects of the Moses-Saunders hydropower dam in the Upper St. Lawrence River which observed 81 wetlands and found that higher levels of total and methylmercury concentrations increased with distance downstream of the dam. While these studies focused on the concentration levels of metals, they impact the nearshore ecosystem, and regulation actions were put into place to mitigate the negative impacts.

While monitoring mercury levels in aquatic wildlife is important, monitoring fish species, in particular invasive species, is researched in the Upper St. Lawrence River. Maracle et al. (2024)

monitored aquatic biodiversity through analysing environmental DNA and seining methods along the Upper St. Lawrence River. Comparing the two methods, they found that eDNA methods located higher amounts of fish species; observed higher species at risk and invasive species; and found that eDNA was an easier way to identify elusive, offshore, and benthic species. While monitoring methods are important, researchers have found round gobies as one of the most invasive species in the Upper St. Lawrence River (Morissette et al. 2018), with multiple research papers focusing on round gobies. Goretzke et al. (2019) observed higher numbers of round goby abundance in both the American and Canadian waters of the Upper St. Lawrence River. They expect that the rate of expansion may increase, but at a slower rate than waterways with calmer waters like Lake Ontario. Other researchers have found similar findings. Astorg et al. (2022) revisited round goby impacts towards fish communities and macroinvertebrate after two decades of their first discovery in 2004 using data from previous studies (Kipp and Ricciardi 2012; Morissette et al. 2018) and empirical surveying results. The research team grouped the time of invasion into intervals of 12 years and earlier, 13 to 16 years, and 17 to 19 years. They were able to show an inverse correlation between round gobies and macroinvertebrates, demonstrating that the invasive species negatively impacted other species.

While invasive species like round gobies are impactful in the Upper St. Lawrence River, research regarding navigation and ship wakes are showing greater relevance within the last couple years as concerns have grown (Schiefke 2023). Research in relation to ship wake throughout the Upper St. Lawrence River has mainly focused hydrodynamics and riverbank erosion induced by ship waves (Gharbi et al. 2010). The research team compared the length of two different vessel sizes and observed that maximum wave height did not necessarily increase with increasing the length of the vessels, and the number of waves in a wave train increased with increasing the length of the vessels. They found that the number of waves in a wave train was more influential towards riverbank erosion compared to the maximum wave heights. Furthermore, Haghighi et al. (2025) observed the suspended sediment from ship wake. Their results demonstrated that wind waves in shallow, unprotected sites deliver consistent turbidity while ship induced waves produce spikes in the suspension sediment concentrations and short term turbidity. Additionally, their research indicated having wave amplitude at exposed site locations compared to the protected site locations. Furthermore, Haghighi et al. (2026) continued research on the effects of ship types and ship sizes using the Upper St. Lawrence River.

Previous research in the Upper St. Lawrence River has demonstrated the importance of nearshore ecology through monitoring concentrations of metals in the ecosystem, surveying and monitoring aquatic wildlife, and ship wake effects. The research conducted in this thesis provides a bridge that gaps two of these three groups: observing and surveying aquatic wildlife with the influence of ship wake.

1.3 Novelty of the Study

While hydrodynamics and sediment transport are the predominant focus of ship wake studies, very limited research has correlated ship wake towards fish communities. Ship wake research predominantly focuses on sediment transport through shoreline erosion, and bed and bank resuspension (Dempwolff et al. 2026; Duró et al. 2020; Gabel et al. 2017; Goertz et al. 2026; Göransson et al. 2014; Joubert and Figlus 2026; Parnell et al. 2007; Rapaglia et al. 2015; Shuster et al. 2020); hydrodynamics (Bao et al. 2026; Shugan and Chen 2022); ship type and size (Haghighi et al. 2026); and the interaction between ship wake and wind waves (Haghighi et al. 2025; Yang et al. 2011). While these primarily focus on other aspects, very few have correlated the effects of ships towards fish community structures (Gutreuter et al. 2006; Huckstorf et al. 2011).

This research focuses on bridging the gap between ship wake and fish community structures. Using the Fish Identification Nearshore (FINS) database, correlations between fish abundance (number of fish) and fish richness (number of fish species) can be found at site locations within the Upper St. Lawrence River. Previous studies monitoring the exposed and protected fish habitats in the Upper St. Lawrence River have shown correlations to exposure; however, the scale of their research was limited to eight site locations and does not directly correlate ship wake while the FINS database includes over 230 site locations with the primary focus of investigating the influence of ship wake.

1.4 Research Objectives

This study aims to assess the FINS database in the Upper St. Lawrence River and to find any correlations with respect to the shipping lane. Fish abundance and fish richness are the two quantifiable metrics used to find correlations. Using regression analysis on the slope of R^2 correlation and three variations of statistical analyses (analysis of variance (ANOVA), Mann-Whitney U, and Kruskal-Wallis H), the goal is to find statistical significance within five different

factors: (1) direct exposure to the shipping lane, (2) the distance to the shipping lane from the sampling site, (3) the coastline geometric classification as either straight shoreline or embayment shoreline, (4) the dominant substrate grain size, and (5) the habitat type based on binary classification as either wetland or non-wetland. The three analysis methods test for statistically significant difference ($p < 0.05$) between the means of the independent groups, and their magnitude is portrayed by their effect size, η^2 .

1.5 Project Contributors

For the research article included in Chapter 2, the field data was collected by the FINS team at the St. Lawrence River Institute, most notably: Matthew Windle, Kate Schwartz, Cassey O'Connor, and Emma Ehrenfeld. Geographical mapping and manipulation, data analysis, and statistical modelling was conducted by the author under the supervision of Drs. Colin Rennie and Ioan Nistor. Chapters 1 and 3 of this thesis and the article in Chapter 2 was written by the author and edited by Drs. Colin Rennie and Ioan Nistor.

2 Ship Wake Influence on Nearshore Fish Community Structure in the Upper St. Lawrence River

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2.1 Abstract

The St. Lawrence River is a navigational waterway used by both commercial and recreational ships. Large ships generate both primary (drawdown) and secondary (wake) wave patterns that travel towards the shorelines, disrupting nearshore habitat. The Fish Identification Nearshore (FINS) database consists of fish surveying, habitat, and physical and water quality data across 230 site locations in the Upper St. Lawrence River. In this paper the FINS database is utilized to identify correlations between proximity to the shipping lane in the Upper St. Lawrence River and the fish abundance (the total number of fish) and fish richness (the number of fish species) found at each sample location. Statistical significance is assessed using analysis of variance (ANOVA) and non-parametric Mann-Whitney U and Kruskal-Wallis testing. The results demonstrated that for sites in direct line-of-sight of the shipping lane there is a significant influence on the fish community for sites within 350 m of the shipping lane. Further, for these exposed sites, shoreline geometry with curvature due to an embayment delivers higher fish richness compared to relatively straight shorelines, as does a dominant substrate of sand. Also, the habitat type (wetland versus rocky shoreline) at the site location plays an important role in fish richness. In summary, straight sites close to the shipping lane with cobble shorelines were found to have reduced fish community diversity, presumably due to the influence of near-shore wave action.

2.2 Introduction

Ships that travel through a body of water generate a wave pattern on the surface of the water, known as ship wake. Previous ship wake research has shown that ship wakes influence various domains, such as shoreline bank erosion, sediment resuspension, increased turbulence nearshore, and negative ecological disturbances (Dempwolff et al. 2026; Duró et al. 2020; Göransson et al. 2014; Haghighi et al. 2025; Joubert and Figlus 2026; Parnell et al. 2007; Shuster et al. 2020). While most studies have investigated the influence of ship wake towards shoreline bank erosion and sediment resuspension, there is a paucity of research on impacts of ship wake on fish communities. This study uses the Upper St. Lawrence River, Canada to address the influence of ship wake towards fish communities.

There are two main components to ship wake, primary waves known as drawdown waves, and secondary waves known as Kelvin wakes. Drawdown waves are created in confined channels when water displacement by the ship leads to water surface depression between the bow (front) and stern (back) of the ship. The drawdown wavelength is a function of the length of the ship, while the wave height is a function of the ship's speed and the ship's cross-section (Dempwolff et al. 2022). Secondary waves were studied as early as 1877, when Lord Kelvin classified the wave shape into two separate patterns: transverse (perpendicular with the ships movement) waves and divergent (parallel with the ships movement) waves (Yang et al. 2011). To this day, these wave patterns are known as Kelvin wakes. Since then, many studies have examined ship wakes. Ship wake hydrodynamics research continues to explore the variability of wake characteristics, such as the wake angle (Shugan and Chen 2022), the pressure distributions (Bao et al. 2026), the influence of ship type and size (Haghighi et al. 2026) and the interaction between and separation of ship wake waves and wind waves (Yang et al. 2011; Haghighi et al. 2025).

Ship wake research has also examined impacts and erosion along the shoreline, including embankments, islands, and ecological areas (Dempwolff et al. 2026; Goertz et al. 2026; Parnell et al. 2007; Shuster et al. 2020). Ship wake erosion can be induced by a variety of boats of different scales, including small recreational boats close to the shoreline (Shuster et al. 2020), massive commercial ships which increases the wave energy of wakes (Dempwolff et al. 2026), and higher speed ships that can impact shorelines from far distances away (Parnell et al. 2007). Many studies have demonstrated that drawdown waves generate strong turbulent surge currents near the shore,

resuspend bed and bank sediments, and cause the bed and bank to erode (Duró et al. 2020; Gabel et al. 2017; Göransson et al. 2014; Haghighi et al. 2025; Joubert and Figlus 2026; Rapaglia et al. 2015).

Herein we evaluate the influence of ship wake on nearshore fish community structure. Very few previous studies have evaluated the ecological and environmental aspects of ship wake impacts on shorelines (e.g., Bishop 2008). Notably, in a width-restricted waterway Huckstorf et al. (2011) observed lower young-of-year fish abundance and species density in reaches with higher ship traffic, with greater impact on species relying on shoreline habitat for rearing (e.g., roach, *Rutilus rutilus*). Additionally, Gutreuter et al. (2006) observed a negative correlation of fish abundance and species density in navigation channels compared to larger secondary channels. More recently, Zajicek and Wolter (2019) observed reduced fish density (particularly for lithophilic fish) in locations with greater commercial and recreational boat traffic in European rivers.

While not specifically focused on ship wake waves, other previous research has demonstrated the impact of waves on fish habitat and fish community structure. Lower fish biomass has been observed at locations with direct wave exposure than in sheltered areas (Depczynski and Bellwood 2005; Friedlander et al. 2003). Júnior et al. (2023) researched how waves impacted the diversity of fish in tropical ocean-exposed sandy beaches and found lower fish abundance, fish richness, and fish biomass on wave-dominated beaches, primarily due to the turbulence. Friedlander et al. (2003) examined the relationship between fish assemblages and their habitat, showcasing that wave disturbance dictated the reef organization. Furthermore, waves generate turbulence which changes the visibility of predators and prey impacting the success of foraging. Two studies have shown that both low and high levels of turbidity from sediment resuspension negatively impacted predation while moderate levels of turbidity were ideal (Gregory and Northcote 1993; Utne-Palm 2004). Studies have also shown that waves can lead to fish fatality by stranding along the shore (Adams et al. 1999) and by dewatering of fish eggs and larvae (Holland 1987). Stoll and Beeck (2012) demonstrated that fish as young as 1 week old will avoid imposed wave conditions by moving to calmer water. To minimize the impact of waves on fish communities, researchers have designed physical (structures) or biological (coral covers) protections for wave mitigation (Friedlander et al. 2003).

The St. Lawrence River is a navigational waterway for commercial and recreational ships. In 1950, the construction of the 306 kilometer long St. Lawrence Seaway between Lake Ontario and Montreal, Canada was constructed. Combined with the Great Lakes, this region has generated 30% of the combined Canada and United States of America economic activity and employment (Seaway 2026). Due to the regular passage of large ships through a relatively narrow waterway, concerns have been raised regarding the influence of ship wake on St. Lawrence River shorelines (Schiefke 2023). Previous research along the St. Lawrence River has examined ship waves (Gharbi et al. 2010) and sediment resuspension (Haghighi et al. 2025). Additionally, ecological research in the St. Lawrence River has primarily investigated the effects of mercury levels in fish (Neff et al. 2013; Osgood et al. 2022), invasive species such as the round goby (Gendron and Marcogliese 2017; Kipp and Ricciardi 2012), and observations of newly found species (De Lafontaine 2005; Hickey and Fowlie 2005). Moreover, Henning et al. (2014) compared fish assemblages at three protected and five open nearshore habitats in the Upper St. Lawrence River. They found that protected and open site locations supported different fish communities; the protected sites strongly associated with higher aquatic vegetation and shallower water while the open site locations with higher fetch and wave exposure had lower vegetation density (Henning et al. 2014).

Herein we present the first study of the influence of ship wake on fish community structure that explicitly considers exposure and proximity of the shoreline to a shipping lane. The study location is the Upper St. Lawrence River, where Haghighi et al. (2025) observed maximum ship wake drawdown wave amplitudes of 0.27 m in an exposed site and 0.08 m in a nearby protected site. Correlations between ship wake and fish communities are examined through the Fish Identification Nearshore (FINS) database that has been produced by the St. Lawrence River Institute in collaboration with the Mohawk Council of Akwesasne. In continuous development since 2015, the FINS database describes the nearshore ecosystem and fish populations in the Upper St. Lawrence River obtained by fish surveys, environmental DNA collection, water quality measurements, vegetation sampling, and drone imagery at more than 230 site locations (Maracle et al. 2024; Windle 2026).

The primary objective of this research is to utilize the the FINS database to examine the influence of exposure to ship wakes on the fish community in the Upper St. Lawrence River. To quantify the relationship, two dependent variables are used: fish abundance (the total count of fish

found at a site location) and fish richness (the total number of species found at a site location). Site locations are classified as either exposed to or protected from the shipping lane to address the issue of direct exposure to the shipping lane. Distances to the shipping lane are calculated to understand the influence of proximity to the sampling sites. Secondary objectives of this study include examination of other factors presented in the FINS database that could influence the impact of exposure of the shipping lane: (1) the coastline geometric classification as either continuously straight shoreline or embayment shoreline, (2) the dominant substrate grain size, and (3) the habitat type based on binary classification as either wetland or non-wetland. The initial hypothesis of this study is fish abundance and fish richness at sites with direct exposure will be inversely related to the distance to the shipping lane due to the proximity of boat wake waves. Secondary hypotheses include: (1) embayment shorelines will deliver higher fish abundance and richness than straight shorelines, (2) finer grain size substrates will deliver higher fish abundance and richness than coarser grain sizes, and (3) wetland habitats will deliver higher fish abundance and richness than non-wetland site locations.

2.3 Methodology

The study area for this research was the Upper St. Lawrence River, primarily between Lake Ontario and Lake St. Francis. The study location spans over 240 kilometres in length, across a body of water with a width of up to 7 kilometres. Due to the large area and most of the site locations being along the shoreline of the river, spatial correlation analyses were not feasible. Instead, a point-based analysis was performed.

The FINS fish community survey method consisted of a standardized three seine hauls procedure, spanning across 60 metres at intervals of 20 metres, placing a bin at each interval (Osgood et al. 2022). A 9.14 metre by 1.83 metre seine with a mesh size of 6.35 millimetres was used to gather fish. At least three trained researchers were employed throughout the procedure, two carrying the seine net from supporting poles and one carrying the mesh from behind to ensure no large debris caught the net. Upon reaching the bin, all fish in the net were placed in the water filled bin, and then the team proceeded to the next two sections and repeated the same procedure. All captured fish were identified and counted, and the first twenty fish of each species were measured. Pictures of each species were taken and then the fish were released back into the river (Ehrenfeld et al. 2024).

The FINS surveying occurred over a 10-year period. Some of the site locations were visited multiple times throughout the years of research. Consequently, these sites had multiple samples collected at nearly the same location but during different years and different months within the year. Each individual survey was treated as an independent sample point in the analysis. This assumption of independence was justified because variance of fish richness or abundance at individual site locations was similar to the variance in the entire data set. For example, the standard deviation of fish richness was 4.23 for all samples in the FINS database (n=611), while at three site locations with multiple samples it was 3.09 (n=12), 4.27 (n=18), and 3.82 (n=11). Further, as described in detail below, longitudinal time analyses found neither correlation nor trend between samples collected at individual site locations, which provided further support for the independence assumption.

To focus on the influence of ship wake, a shipping lane throughout the Upper St. Lawrence River was drawn in ArcGIS using the buoy locations from nautical charts. Distances between the shipping lane and the individual site locations were calculated. For this study, sample sites were classified as either exposed to or protected from (e.g., sheltered by islands) the shipping lane. Figure 2 illustrates the study area for the Upper St. Lawrence River between Lake Ontario (west) and Lake St. Francis (east) with exposed site locations coloured blue and protected site locations coloured orange. Habitat type is illustrated as either wetland (circles) or non-wetlands (triangles). Due to the map scale, some protected site locations may look exposed to the shipping lane; however, based on the shoreline geometry and small islands underneath the symbols, those site locations are protected. The shipping lane polygon is coloured in lime green.

Statistical analyses were performed using IBM SPSS statistics software. Depending on the distribution of the data for fish abundance and fish richness, three different methods were used to test for statistically significant difference ($p < 0.05$) between the means of the independent groups in relation to the dependent variable (fish abundance or fish richness). If the distribution was normal, an analysis of variance (ANOVA) method was conducted. Meanwhile, if the distribution was skewed, a non-parametric method was used depending on the number of groups within the independent variable. If the independent variable had two categories, the Mann-Whitney U method was used, while the Kruskal-Wallis H method was used for any variable with more than two categories. Accompanied by the p-value, an effect size value, η^2 , was used to present the

magnitude regardless of the scale of each independent variable. While there are multiple possible metrics to consider effect sizes, η^2 was used throughout the study as it is an efficient and effective way to compare effects within the study between different variables (Lakens 2013).

Assumptions are required when using statistical models. For the ANOVA model the distribution must be a normal distribution, and for both ANOVA and the non-parametric tests the variance within the data must be equal between independent variables (Mendenhall and Sincich 2007). To ensure these assumptions were satisfied, box-and-whisker plots (i.e., boxplots) were used throughout this study to demonstrate the distributions of fish abundance and fish richness categorized by habitat type, coastline geometry, and dominant substrate. The boxplots illustrate: (1) the minimum, (2) the first quartile (25th percentile), (3) the median, (4) the third quartile (75th percentile), and (5) the maximum. Furthermore, any values outside of the minimum and maximum (shown by the bars attached to the box – or the “whiskers”) are outliers in the dataset.

The FINS surveys were collected over a ten-year period at different times of the open water season. It is possible that any seasonal or longitudinal trends in fish abundance or richness may have impacted results. Consequently, influence of sampling time was tested. ANOVA analysis on the entire data set, protected sub-set, exposed sub-set, and at single sites (e.g., n=18, Cornwall Island South Inlet) found no significant differences in means of fish abundance or richness between the months or years of sampling, so time of sampling was not considered in the subsequent analyses.

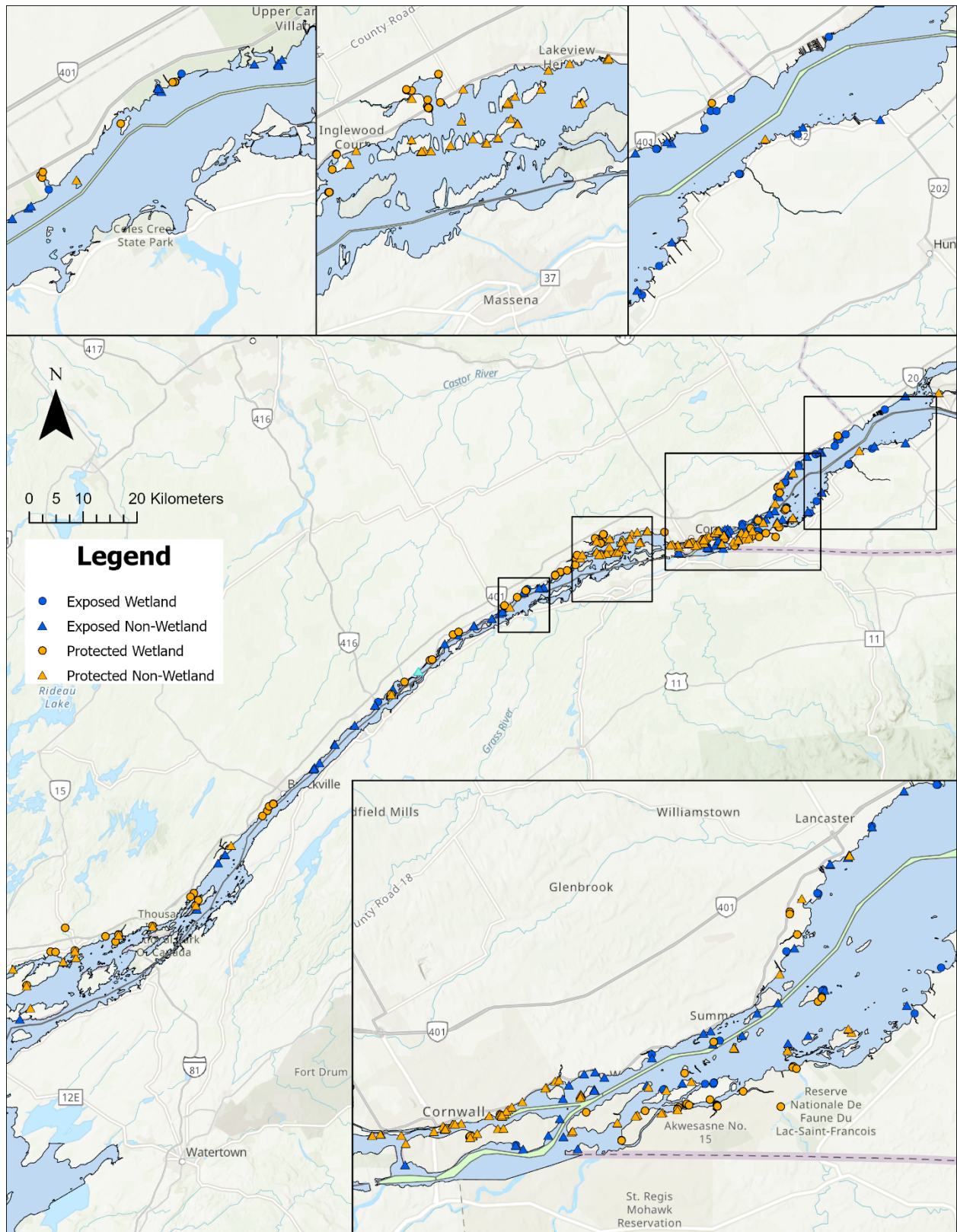


Figure 2. Map of St. Lawrence River between Lake Ontario and Lake St. Francis with site locations split between wetlands (circles) and non-wetlands (triangles) and exposed site locations (blue) and protected site locations (orange).

2.4 Results

Prior to analysing the database, the site locations were classified as either exposed to or protected from the shipping lane. To classify the site locations, a line of shortest distance from the sample location to the shipping lane was generated. Site locations classified as exposed to ship wakes had direct exposure with no land interfering with the shortest line. Otherwise, the site locations were classified as protected from the shipping lane. For the FINS database, roughly 42.5% of sample locations were categorised as exposed to the shipping lane whereas roughly 57.5% were categorised as protected.

2.4.1 Distance to the Shipping Lane

Figures 3a and 3b illustrate for exposed and protected site locations the values of fish richness and fish abundance, respectively, within 500 metres of the shipping lane. In Figure 3a, there is a positive correlation between fish richness and the distance to the shipping lane for the exposed sample locations, indicating that sites closer to the shipping lane had lower fish richness. This correlation is strongest for sites closer to the shipping lane. Considering all exposed sites within 200 m, 300 m, 400 m, or 500 m of the shipping lane, the R^2 values (regression slope, p-value, sample size n) were 0.785 (55.4, 0.114, 4), 0.300 (30.0, 0.024, 18), 0.147 (2.35, 0.010, 52), and 0.098 (13.9, 0.015, 64). Exposed regression lines for fish richness can be found in Figure 3a. For exposed sites within 200 m the R^2 was high and regression slope was very large, but the correlation was not quite significant due to small sample size. No significant correlations were found when considering all exposed sites within 600 m or more of the shipping lane. Based on these results, it can be inferred that there was a negative correlation between fish diversity and proximity to the shipping lane. Importantly, fish richness was reduced for exposed sites within 500 metres of the shipping lane in the FINS dataset. This is the first study to identify the distance to the shipping lane at which impact on nearshore fish community structure can be observed. This result aligns with previous literature. Huckstorf et al. (2011) demonstrated decreased species diversity in higher traffic intensity areas compared to other reaches and Zajicek and Wolter (2019) demonstrated that both commercial and recreational ships negatively influence nearshore fish communities. Additionally, from an ecological standpoint, other literature has shown that larger fish prefer wave-exposed site locations compared to smaller fish who prefer calmer water (Depczynski and Bellwood 2005; Henning et al. 2014).

In Figure 3b, it appears that there is no correlation between fish abundance and the distance to the shipping lane. Nonetheless, a significant correlation was observed for sites within 200 metres from the shipping lane with an R^2 value of 0.997 (2538, 0.002, 4). The exposed regression line for fish abundance within 200 metres can be found in Figure 3b. Like fish richness, this demonstrates a negative correlation between fish abundance with proximity to the shipping lane. However, no significant correlations were observed for fish abundance when considering all sites within further distances from the shipping lane.

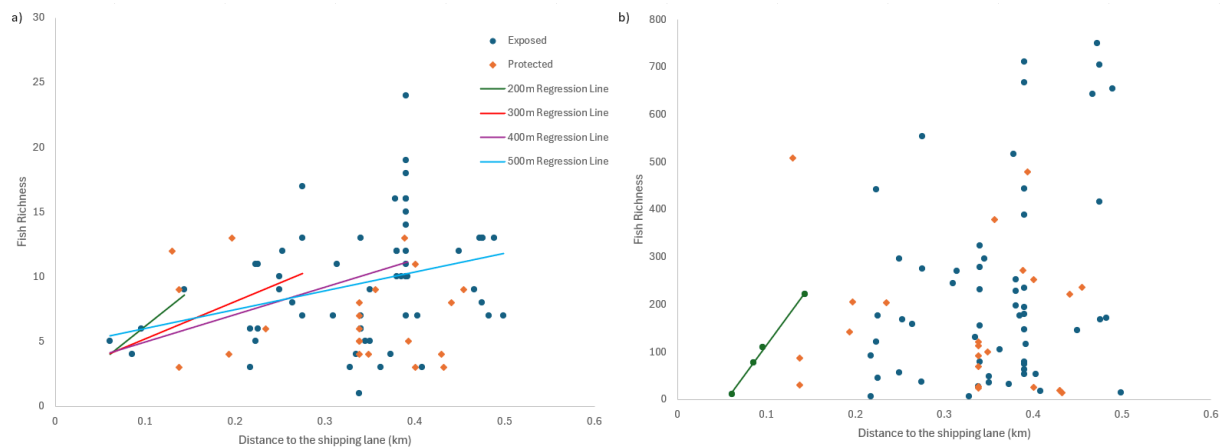


Figure 3. Distribution of (a) fish richness and (b) fish abundance by the distance to the shipping lane.

Contrary to exposed sites, no significant correlations were observed for protected sites between fish abundance or fish diversity and distance to the shipping lane. Presumably, this is because the nearshore ecosystem is sheltered from incoming ship wake waves at protected sites. This means that other factors are driving the number of fish and fish diversity found at protected site locations. Previous literature has demonstrated that the physical habitat has a strong influence on fish community structure (Moustaka et al. 2024; Wang et al. 2022).

ANOVA was also employed to compare mean values of both fish abundance and fish richness between all protected sites and exposed sites at various distances from the shipping lane. To complete this analysis, the exposed site locations between 200 metres and 1 kilometre from the shipping lane were increased at increments of 50 metres to generate sample populations for comparison to all protected site locations. All protected sites were considered a single sample

population since protected sites were not influenced by the shipping lane (Figure 3). Mean fish richness in exposed sites within 350 m from the shipping lane (7.77) was statistically significantly different than the mean fish richness in protected sites (9.60) (p-value = 0.018, effect size value $\eta^2 = 0.014$). The upper and lower 95% confidence interval bounds for the mean fish richness for exposed site locations within 350 m of the shipping lane were 6.38 and 9.15, respectively, whereas the protected site location bounds were 9.19 and 10.02, respectively. Additionally, two other distances for mean fish richness (200 metres and 250 metres) had nearly significant differences (p-values of 0.079 and 0.083, respectively). Overall, these results suggest that proximity to the shipping lane had negative influence on fish richness at exposed site locations relative to protected site locations. Conversely, no distance delivered statistically significant results for fish abundance.

2.5 Other Habitat Factors

The primary objective of this study is to identify impact of exposure to the shipping lane, but it is possible that other habitat features that modify the impact of ship wake may moderate this effect. We tested three possible factors: shoreline geometry (straight vs embayment), substrate (range of finer sediments such as sand and silt to coarser sediments such as cobble and boulders), and habitat type (wetland vs non-wetland). We tested for this effect on the population of sampling locations with direct exposure to the shipping lane within 1 km. The larger distance than 500 m was selected to increase sample size to increase statistical power.

2.5.1 Shoreline Geometry

The shoreline geometry was classified into binary categories of continuous straight shorelines and embayment shorelines. A straight site location has consistent direction before and after the site location. An embayment shoreline surrounds the surveyed area of the site location.

Figure 4 demonstrates the distribution of fish richness in the Upper St. Lawrence River for exposed site locations within 1 kilometre to the shoreline. The distributions of fish are split between straight and embayment shorelines. Mean fish richness in embayment sites (10.91) was statistically significantly greater than the mean fish richness in straight sites (8.53) (p-value = 0.005, effect size $\eta^2 = 0.064$). The upper and lower 95% confidence interval bounds for the mean fish richness for straight shorelines were 7.37 and 9.70, respectively, whereas the embayment site locations bounds were 9.86 and 11.96, respectively. Conversely, fish abundance did not yield

statistically significant results ($p\text{-value} = 0.141$); however, like fish richness, the mean fish abundance at straight shorelines (54.7) was lower than embayment site locations (64.5).

Due to wave transformation processes in embayments with shoreline curvature and relatively shallow depths (Van Leeuwen et al. 2000), the exposed embayment shorelines possibly act as pseudo-protection against the approaching ship wake which allows the embayment areas to have calmer waters relative to the exposed straight shorelines. Since the embayment shorelines may act as pseudo-protection, more stable habitat can develop including increased vegetation, lower turbulence and less sediment resuspension and scour.

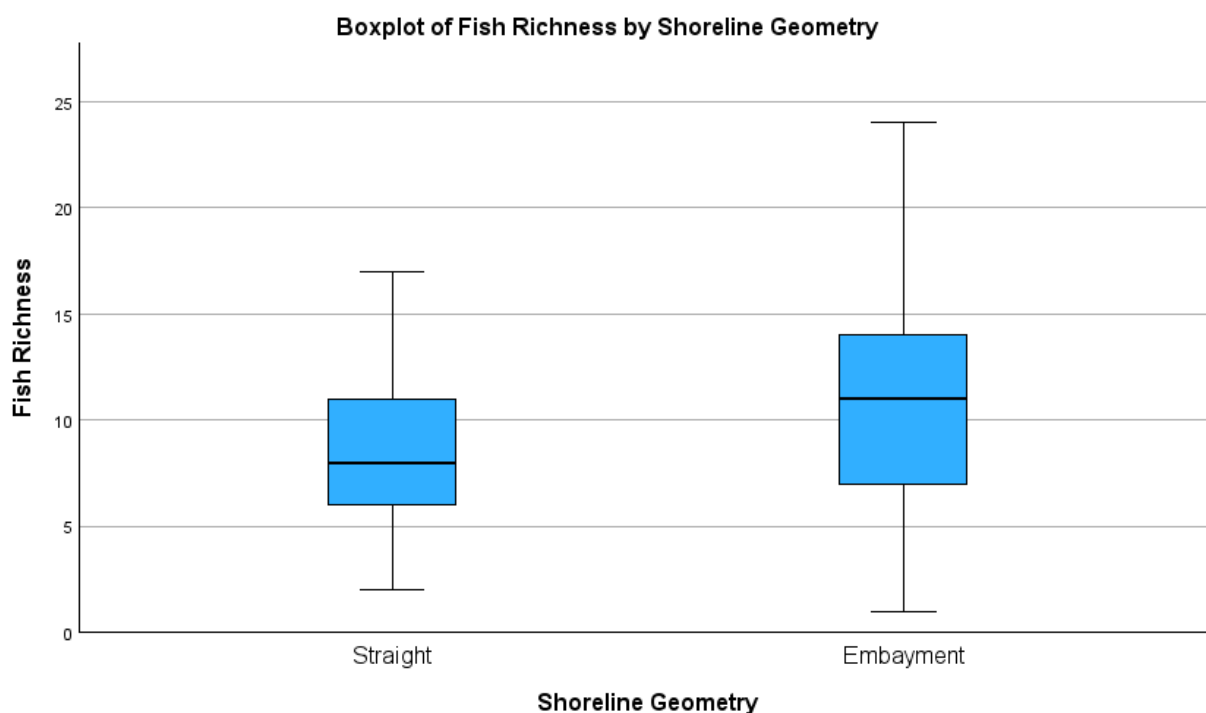


Figure 4. Fish richness distribution for straight and embayment shoreline at exposed site locations within 1 kilometre from the shipping lane in the Upper St. Lawrence River.

2.5.2 Dominant Substrate

The FINS dataset records the substrate found at each survey location on a percentage scale for clay, silt, sand, gravel, cobble, boulders, and organics. Site locations dominated by vegetation are classified as organics. The FINS database considers various mixture classifications, but to

ensure each class has sufficient sample size, herein dominant substrate is defined as the substrate size class with the highest percentage. Figure 5 illustrates the fish richness for exposed sites within 1 kilometre of the shipping lane based on their dominant substrate.

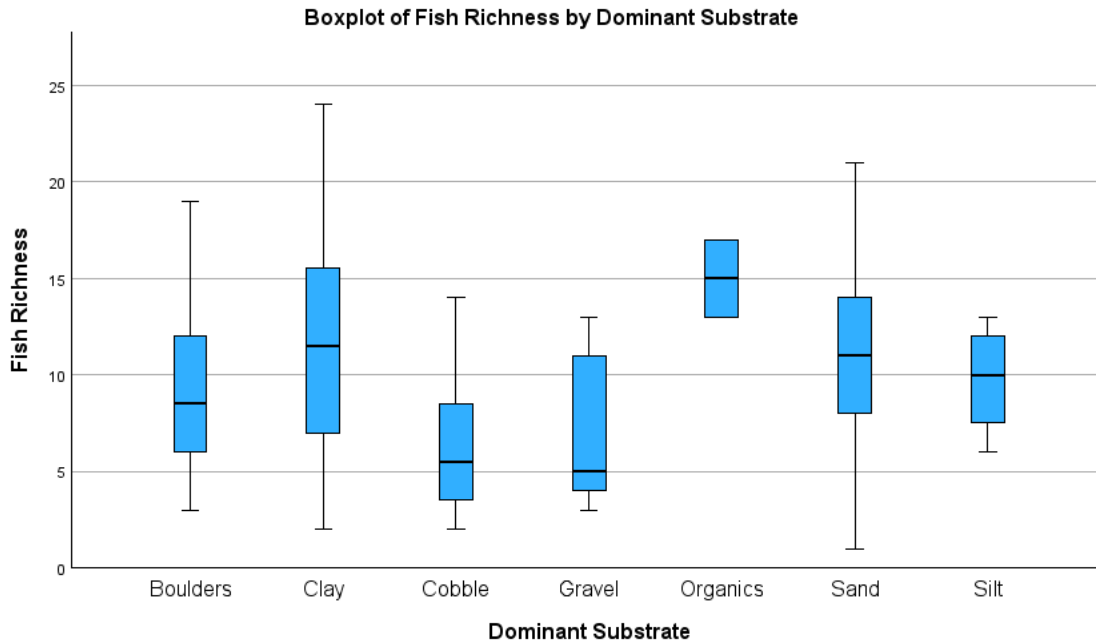


Figure 5. Fish richness distribution based on dominant substrate for exposed sites within 1 kilometre from the shipping lane in the Upper St. Lawrence River.

ANOVA results demonstrated statistically significant differences (p -value = 0.004, effect size $\eta^2 = 0.162$). Tukey testing was used to determine which values within the seven groups were significantly different from each other. Based on the results, the mean values for sand (11.00) and cobble (6.42) were significantly different. Two other dominant substrates (clay and organics) had higher mean richness values (11.75 and 15.00, respectively); however, the sample sizes (8 and 2, respectively) were not large enough to obtain robust statistics. This result demonstrates that for exposed site locations within 1 kilometre from the shipping lane, finer substrates yield higher fish richness than coarser substrates. Fish abundance had a similar trend; however, it did not result in a statistically significant difference (p -value = 0.061) with smaller grain sizes (clay and sand) having higher fish abundance (66.6 and 66.8, respectively) compared to larger grain sizes (cobble and gravel) with lower fish abundance (37.5 and 42.06, respectively). Since finer substrates tend to promote more vegetation, these results may suggest that vegetation at a site can help attenuate

wave action and/or increase habitat complexity. Previous studies have found that more complex habitats support higher fish abundance and diversity (Gratwicke and Speight 2005).

2.5.3 Habitat Type

A binary habitat type between wetland and non-wetland is classified in the FINS dataset: 228 site locations (roughly 37%) are categorised as wetlands whereas 383 site locations (roughly 63%) are categorised as non-wetlands. As expected, wetland sites had significantly higher fish richness than non-wetland sites ($p < 0.001$, $\eta^2 = 0.029$); conversely, fish abundance did not ($p = 0.310$). This result aligns with previous literature, where Gratwicke and Speight (2005) and Moustaka et al. (2024) demonstrated that habitat complexity is a primary reason for high fish abundance and diversity. Additionally, Wang et al. (2022) observed a stronger influence of habitat type than other parameters such as water quality and riparian conditions. The shallow open water and vegetation characteristics of wetland sites create diverse habitats that support a wider range of fish species compared to non-wetland sites.

Focussing on exposed sites, Figure 6 illustrates the distribution of fish richness for sites with exposure to ship wake within 1 kilometre from the shipping lane categorized by habitat type. Contrary to the hypothesis, there was no significant difference in mean fish richness at exposed wetland site locations (9.31) than exposed non-wetland sites (10.12) ($p\text{-value} = 0.542$, effect size $\eta^2 = 0.003$). The 95% confidence interval for wetland sites ranged between 7.27 to 11.35, meanwhile the non-wetland sites ranged from 9.23 to 11.01. Fish abundance was also tested; however, the differences in means between wetland (60.00) and non-wetlands (61.12) was very small with an insignificant difference ($p\text{-value} = 0.913$). These results may have been due to low statistical power: there were only 13 samples for exposed wetland site locations within 1 kilometre of the shipping lane. Obtaining more samples would increase the understanding as to whether wetland habitat can ameliorate the impact of ship wake on fish community structure.

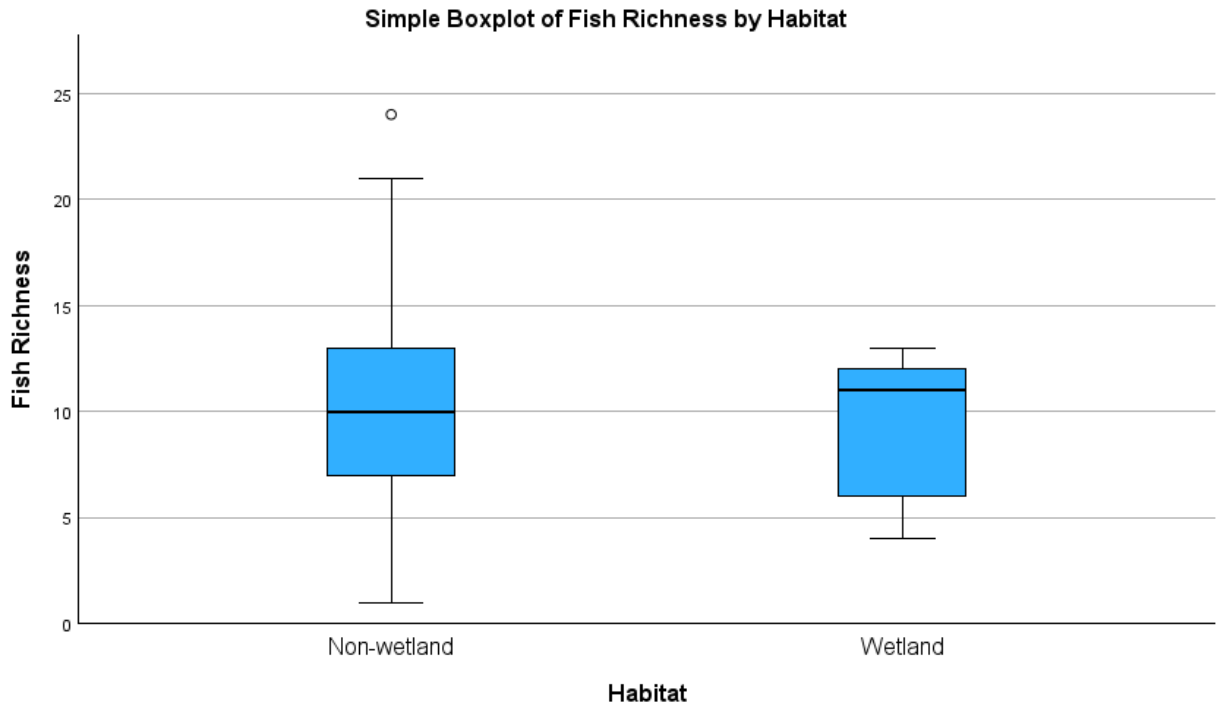


Figure 6. Fish richness distribution between non-wetland and wetland exposed site locations within 1 kilometre from the shipping lane in the Upper St. Lawrence River.

2.6 Discussion

The findings of this study demonstrate that ship wake waves have significant impact on nearshore fish ecosystems within the Upper St. Lawrence River. The results support the original hypothesis for fish richness; conversely, tests for fish abundance were not statistically significant. For sites with direct exposure to ship wake, fish richness was found to decrease with proximity to the shipping lane. The magnitude of the regression slopes for distances from 200 metres to 500 metres decreases as the proximity to the shipping lane increases, demonstrating the influence of ships is stronger closer towards the shoreline. The correlation becomes null for distances exceeding 500 metres. Importantly, fish richness was reduced for exposed sites within 350 metres of the shipping lane compared to protected sites in the FINS dataset. These results suggest fish ecosystems are influenced within 500 metres of the shipping lane. This is likely due to the decrease in wave energy as the distance to the shipping increases. This is the first study to determine the distance to the shipping lane at which impact on nearshore fish community structure can be observed.

Previous research has shown effects on the fish community in navigational waterways (Gutreuter et al. 2006; Zajicek and Wolter 2019) and in sites directly exposed to wind waves (Depczynski and Bellwood 2005; Friedlander et al. 2003). This study supports and extends these studies by assessing the impact of direct exposure to ship wake waves. A previous study in the Upper St. Lawrence by Haghighi et al. (2025) demonstrated that site locations with direct exposure have higher wave amplitudes compared to protected site locations. The impact of drawdown waves due to passing ships was readily discernable during FINS surveys in the Upper St. Lawrence River. Initially, the water level would visibly decrease along the shoreline as water was drawn towards the ship, and fish were observed to be transported offshore by this flow. As the ship passed the sampling location, a strong release of wave energy would propagate towards and crash on the shoreline, disrupting the nearshore fish community. Usually, fish abundance and richness were found to be zero immediately following such an event, and these samples were discarded due to the temporary disturbance event. The present analysis demonstrates that direct exposure to ship wake waves has an enduring impact on the nearshore fish community.

Additional research would be required to determine the mechanisms by which ship wake waves impact the nearshore fish community. Ship wake waves may influence fish through various physical mechanisms such as higher local velocities, increased turbulence, inconsistency of water levels, increased sediment resuspension, greater bank and bed erosion, and reduction in swimming performance for fish. In the Upper St. Lawrence River, Haghighi et al. (2025) found that exposed site locations had higher wave amplitudes, and in general the highest turbidity due to sediment resuspension was observed at exposed site locations during drawdown waves, while the lowest turbidity occurred at protected sites. Similarly, Göransson et al. (2014) demonstrated that maximum turbidity levels are a function of drawdown height and a negative function of water depth. Studies have shown that turbidity levels affect the visibility of both predators and prey (Gabel et al. 2017). A study in Norway found a positive effect for intermediate turbidity levels for smaller larvae while larger turbidity levels had a negative impact, and higher turbidity levels allowed more attacking for the larger larvae (Utne-Palm 2004). Another study in Canada demonstrated that higher turbidity levels and clear water scenarios reduced foraging rates for all tested species while the intermediate levels of turbidity delivered the highest amount of foraging (Gregory and Northcote 1993). Finally, the increase in wave velocity from ships was found to

cause a negative impact towards swimming performance fish communities where they needed to migrate to calmer waters to have sustainable habitat (Kucera-Hirzinger et al. 2009).

Another factor that could influence the nearshore fish community is the noise and vibrations of the navigating ships. Vibrations and noise are two factors that influence the auditory systems of fish. Various research has demonstrated that noise pollution negatively impacts fish communities. Jägerbrand et al. (2019) found that noise in the aquatic environment can originate from a variety of sources, primarily between 10 Hz to 1 kHz. The researchers describe shipping noise as non-uniform and varied based on ship type and weather conditions. Various other studies have demonstrated the impact of noise on fish communities. Many fish species use auditory information to locate predators and prey, to communicate, and for habitat selection. Anthropogenic noise (noise induced by human activity) can have a negative effect on fish behaviour and physiology (Cox et al. 2016). Additionally, Hou et al. (2025) modelled that fish were vulnerable to noise pollution when it was increased by 60%. Four physiological processes were impacted by the increase in noise pollution: food intake, energy expenditure, mortality, and reproduction. Voellmy et al. (2014) demonstrated that foraging and food consumption were negatively impacted by noise pollution; however, they mention that the magnitude of the noise is species specific. Finally, Nedelec et al. (2016) found that after two days of exposure to motorboat noises, hiding increased for coral reef fish. Surprisingly, the fish would adapt to the noise, and it no longer affected them after one to two weeks. This study demonstrated that tolerance ranges for fish change after a while.

Secondary analyses regarding shoreline geometry, dominant substrate, and habitat type were performed in this study on sites with exposure to ship wake within 1 kilometre of the shipping lane to assess whether site habitat features can modify the impacts of ship wake. As expected, exposed embayment shoreline geometries had higher fish richness than exposed straight shorelines. Additionally, finer grain size sediment had higher fish richness compared to the larger grain sizes. However, contrary to the hypothesis, fish richness for wetland sites within 1 kilometre of the shipping lane was not significantly different than for non-wetland sites. Differences in fish abundance for all three secondary analyses were statistically insignificant.

Results for exposed embayment site locations supported the original hypothesis where higher fish richness ($p=0.006$, $\eta^2=0.064$) was found at embayment locations compared to straight

shorelines. This is likely due to wave transformation within the embayment. In general, a curved embayment offers calmer water compared to an exposed straight shoreline. Previous research has demonstrated that sheltered embayment site locations reduce the influence on approaching waves which results in lower wave energy and other factors such as erosion and sediment transport (Daly et al. 2014; Nobre Silva et al. 2024; Uphues et al. 2026).

For dominant substrate at exposed sites, finer grain sizes had higher fish richness and abundance than coarser grain sizes, even though finer grain sizes are more likely to resuspend. Possibly, finer grain sizes supported more vegetation and thus more complex habitat. Different fish prefer different grain size distributions in their habitat. For example, (Stoner and Abookire 2002) found that smaller fish prefer smaller grain sizes to bury and camouflage themselves from predators. Meanwhile, larger fish use coarser grain sizes to spawn eggs (Kondolf and Wolman 1993). While different grain sizes are required by different species and age classes of fish, the results suggest fine-grained nearshore habitat in Upper St. Lawrence River supports a greater diversity and abundance of smaller-sized fish. Looking at the 2024 FINS data, the fish with highest abundance throughout that year were Bluntnose minnows (*Pimephales notatus*), Round (*Neogobius melanostomus*) and Tubenose (*Proterorhinus semilunaris*) gobies, and Banded killifish (*Fundulus diaphanus*), all three of which are relatively small fish. However, there is a possible bias in this assessment as the sand sub-set had the highest number of samples by a large margin (151 samples for sand, next highest being 23 for silt).

Contrary to the original hypothesis, mean fish richness in exposed wetland habitats and exposed non-wetland habitats were not significantly different. Likewise, fish abundance did not obtain a statistically significant result. This result is contrary to what is found in previous research. The expected result would demonstrate that exposed wetland site locations deliver higher fish richness compared to non-wetland site locations. The large abundance of aquatic vegetation at wetland sites compared to non-wetland sites attenuates waves, decreasing the amount of energy acting against the nearshore fish communities. Indeed, coastal aquatic vegetation such as salt marshes (Zhu et al. 2026) and mangroves (Chen et al. 2026) are used to attenuate waves as green solutions. Additionally, waves enrich the nutrients in the surrounding area through mixing (Tensubam et al. 2024). These studies demonstrate that wetland sites compared to non-wetland sites enable the vegetation to attenuate waves while still allowing enough energy to induce

circulation of nutrients. However, no corresponding influence on the fish community at exposed sites as found in our study. This is likely due to the difference in sample sizes between wetland (13) and non-wetland (108) site locations. Obtaining further sampling for exposed wetland sites within 1 kilometre from the shipping lane would help us understand the relationship with stronger statistical power.

Effect sizes were obtained throughout the statistical analyses of each factor: distance to the shipping lane ($\eta^2 = 0.014$), shoreline geometry ($\eta^2 = 0.064$), dominant substrate ($\eta^2 = 0.162$), and habitat type ($\eta^2 = 0.003$). Based on the effect sizes obtained, it is expected that the dominant substrate has the strongest influence towards the results as the effect size is the largest of the group. However, based on the distribution of sampling, the dominant substrates varied between subsets. The sand subset had the largest number of samples; meanwhile samples such as organics and clay had very little sampling of 2 and 8, respectively. Despite the difference in sample sizes for each subset in substrate, the large effect size relative to the other factors demonstrates that the substrate could be one of the stronger influences on fish richness found at site location. The shoreline geometry demonstrates the next highest effect size. The result demonstrates that the pseudo-protection of the shoreline may attenuate wave hydrodynamics, giving a sheltered and calmer area for fish to inhabit. The third effect size is the distance to the shipping lane. The effect size is small; however, the small sample sizes within close proximity to the shipping lane may influence the magnitude of the result. As seen previously, the strongest correlation for exposed site locations is within 200 metres for both richness and abundance. Unfortunately, this distance did not obtain a statistically significant result, as the sample size is only four. If there were more samples at closer distances than 350 metres (i.e. 200 metres or 250 metres), it would be expected to have a higher magnitude as the difference between the means of the exposed and protected shorelines would be larger than the difference found at 350 metres. Finally, the factor with the lowest effect size is the habitat type. This result is surprising. When examining the entire dataset, it is found that the wetland site locations have higher fish richness than non-wetland site locations. This result is expected. However, when concentrating on the exposed site locations, the result is changed and the wetland site locations have lower fish richness than non-wetland site locations. The small effect size demonstrates that the difference between wetland and non-wetland site locations is a subtle difference despite having a statistically significant result.

In this study, there are multiple factors that limit the understanding of the results. The first limit was the relatively small number of sampling site locations at a short distance from the shipping lane. Small sample sizes limited statistical power of tests concerning site exposure at certain distances from the shipping lane, including testing of secondary hypotheses regarding dominant shoreline configuration, substrate and habitat type. Usually, ANOVA and other statistical methods require sample sizes of 30 or more for a robust analysis (Montgomery et al. 2001), especially if populations have large variance. Additionally, the primary results demonstrated that the exposure to site locations had little to no effect on fish richness at distances greater than 500 metres, whereas the secondary analyses needed to use exposed site locations within 1 kilometre to increase statistical power. Increasing the number of samples within 1 km may resolve this discrepancy.

Another limitation is the different number of samples taken at individual locations throughout the Upper St. Lawrence River. As mentioned previously, some site locations were measured up to 18 times while other site locations were only measured once. While the standard deviation across the entire dataset was similar to the standard deviation found at individual site locations, and thus multiple samples collected at single sites were considered independent, surveying at the same site location multiple times may involuntarily cause pseudo-replication which may result in site locations with a higher sampling rate having a stronger influence on the results.

Thirdly, other than the regression for exposed sites within 200 m of the shipping lane, none of the tests for fish abundance obtained statistically significant results. This is likely due to two inter-related reasons: (1) the distribution of fish abundance was skewed with high variance, so non-parametric testing was used, and (2) high abundances of invasive species throughout the Upper St. Lawrence River. The high variance within the fish abundance surveys demonstrated that some site locations had very few fish while others had many. This is likely due to the second reason, the invasive species. Invasive species can heavily influence the number of fish found at a location since they usually lack a natural predator and once they invade a site they can generate a large population. Round gobies have been examined by a variety of researchers (Goertz et al. 2026; Kipp and Ricciardi 2012; Morissette et al. 2018) demonstrating their invasive nature and increasing population in the Upper St. Lawrence River. In a report on invasive species in the Upper

St. Lawrence River in 2024 from the FINS team (Ehrenfeld et al. 2024), they found that round gobies were present in roughly 97% of their site locations, with the second highest overall abundance. Likewise, they found that only five species comprised just over 63% of the fish surveyed while the remaining 43 species made up just 37%. The five dominant species each had a total abundance count over 1500, and if one of the five dominant species was present at a site, it tended to have high abundance at the site. The high variance of fish abundance found at site locations throughout the Upper St. Lawrence River can explain why fish abundance results were not statistically significant.

The different species of fish at each sampling location is possibly an important factor that has not been considered in the present analysis. Different species of fish prefer different ecosystems (Kovalenko et al. 2018). Rosenfeld (2003) demonstrated that different species correspond to different habitats depending on their life stage. Another study demonstrated that larger fish were predominant in areas exposed to wind waves whereas calmer waters were preferred by smaller fish (Depczynski and Bellwood 2005). Henning et al. (2014) showed that different species require different habitats in the Thousand Islands region in the Upper St. Lawrence River. They found that protected site locations supported a diverse range of photophilic species that preferred largely vegetated habitats, whereas *Nitropis* sp. minnows preferred open and exposed site locations due to wind exposure and firmer substrates (Henning et al. 2014). Given different species have different preferences, future research should investigate the species data within the FINS dataset.

Several other factors are included in the FINS dataset that have not been explored. Water quality parameters such as dissolved oxygen levels, pH levels, turbidity, and hydraulic conductivity are collected by the FINS researchers. In the FINS dataset, the dissolved oxygen levels, pH levels and hydraulic conductivity levels are all relatively small ranges. Due to the small ranges, it seems unlikely that they would contribute to significantly different fish abundance or richness. Overall, we expect the factors analysed herein (distance to the shipping lane, wetland habitats, embayment shorelines, and finer sediments) to have more influence. Water quality parameters do affect the aquatic habitat; however, other studies have shown that physical habitat plays a stronger role for fish communities compared to water quality parameters (Moustaka et al.

2024; Wang et al. 2022). Nonetheless, the possible negative influence of turbidity on the nearshore ecosystem, as discussed earlier in this paper, should be explored further.

2.7 Conclusion

This study focused on the influence of ship wake waves on fish communities in the Upper St. Lawrence River. Impacts on fish richness and abundance were examined with respect to exposure and the distance to the shipping lane, habitat type, shoreline geometry, and dominant substrate in the Upper St. Lawrence River. This study demonstrated that (1) fish richness at sites with direct exposure was inversely related to the distance to the shipping lane, and (2) exposed sites within 350 m of the shipping lane had significantly lower fish richness than protected sites. Additionally, for exposed sites within 1 km of the shipping lane (3) an embayment shoreline geometry had higher richness compared to a straight shoreline, (4) sites with finer substrate (sand and clay) yielded higher richness than coarse substrate (cobble and gravel), (5) richness in wetland habitats was not found to be significantly different than in non-wetland habitats, and (6) fish abundance did not deliver statistically significant results.

While wave exposure, habitat type, shoreline geometry, and dominant substrate are previously explored variables for fish ecology, this study provides the first assessment of the distance to the shoreline from a commercial shipping lane in a confined waterway at which impacts on a nearshore fish community can be observed. More broadly, this study advances our understanding of how ship wake waves influence nearshore ecosystems and their respective habitats in the Upper St. Lawrence River while bridging the disciplines of coastal engineering and aquatic ecology.

3 Thesis Conclusion

This work illustrated components of the FINS database using geographical and statistical analyses. Regression analysis on the slope of R^2 correlation, ANOVA, Mann-Whitney U, and Kruskal Wallis H testing were used to determine statistically significant results by comparing the mean value of fish abundance and fish richness for four independent variables.

Initial results suggested that close proximity from the shipping lane to site locations delivered less fish diversity based on the R^2 correlation value of 0.785 for site locations within 200 metres. Based on the R^2 regression analyses, site locations from 300 to 500 metres for fish richness were statistically significant ($p < 0.05$); however, the site locations within 200 metres were not. This is likely due to the lack of sample points ($n=4$) for 200 metres. Furthermore, as the distance increased, the magnitude of the correlation became much weaker, resulting in an R^2 value of 0.098 by 500 metres. Fish abundance obtained a statically significant result at 200 metres ($p=0.002$) with an R^2 value of 0.997. Conversely, the remaining distances were not significant. Upon further investigation, the comparison of exposed site locations at staggered distances against the protected site locations delivered a statistically significant result at 350 metres ($p = 0.018$, $\eta^2 = 0.014$), meanwhile both shorter and longer distances did not.

Secondary results for exposed site locations within 1 kilometre to the shipping lane were analysed for the shoreline geometries, dominant substrates, and habitat types. The exposed embayment shorelines delivered a statistically significant result for fish richness ($p = 0.005$, $\eta^2 = 0.064$) and fish abundance did not yield a statistically significant result ($p = 0.141 > 0.05$). Additionally, the smaller grain sizes (sand and clay) had a strong influence on the fish richness ($p = 0.004$, $\eta^2 = 0.162$) and fish abundance nearly had a statistically significant result ($p = 0.061$) compared to other dominant substrates with larger grain sizes (cobble and gravel). Finally, contrary to the hypothesis, there was no statistically significant difference between wetland and non-wetland site locations for fish richness ($p = 0.542$, $\eta^2 = 0.003$) and fish abundance ($p = 0.913$).

These results improve the understanding of the nearshore ecosystem, allowing future researchers to build upon and use this research to compare to future research. The result generated from the shipping lane analyses allows future researchers to use the 350 metres as a threshold to start exploring field data within this range. Additionally, the strong R^2 correlation for shorter

distances allows researchers to survey more data within close proximity of the shorelines and combine it with the FINS data to have an ample size of data to have reliable results. Furthermore, the results obtained from various factors including shoreline geometry, dominant substrate, and habitat type have reflected what has been researched. The dominant substrate demonstrated that the smaller grain sizes were favourable; however, previous research has shown that more complex environments are favourable for a higher fish richness (Gratwicke and Speight 2005). Limiting the dominant substrate to one substrate when site locations are filled with multiple substrates limits the understanding of the result. However, the results demonstrated the effect of the substrate towards the site locations richness was significant as the richness had the strongest effect size in the entire study. While the habitat type across the entire dataset correlated with the data found in Henning et al. (2014) where different fish preferred the habitat types with large amounts of vegetation, similar to the wetland habitats, data for exposed site locations within 1 kilometre did not.

While most of the results have aligned with previous research, it has also improved the understanding towards the influence of ship wake against the nearshore habitat in terms of exposure to the shipping lane and distance from the shipping. The correlations for fish richness towards the shipping lane have been addressed through proximity to the shipping lane, exposure to shoreline geometries, exposure to the dominant substrate, and exposure to habitat types. Previous studies have shown some of the issues relating navigation towards the nearshore ecosystem, but future research is required to have a deeper understanding of that ship wakes impacts on the nearshore ecosystem.

3.1 Limitations

This research has some limitations. The biggest limitation is the lack of ship wake data from the FINS sample points. Physical water data obtainable via data loggers at accompanied FINS site locations should be obtained to support the statistical results. Until there is direct ship wake data, the results obtained from this study can only be associated with correlation rather than causation. At this moment, there are a couple of pre-existing site locations within the Upper St. Lawrence River which can be used to further the understanding. Using the data obtained from the loggers, a stronger understanding of pressure distributions and water levels can assist in isolating the wake distributions over time.

Another limitation to this study is found based on the number of samplings completed at a single site location. Each sample was taken as their own data point during this study since the standard deviation found at individual site locations across the dataset were very similar to the overall standard deviation of the entire dataset. Despite this, some site locations were sampled up to 18 times while other sites were only done once. The larger number of samples completed may deliver pseudo-replication and have a stronger influence on the results relative to the site locations with only one sample.

Another limitation with the field work stems from variability within the surveying conditions. The temperature and climate are both impactful. Variability is expected across ten years of surveying. While time effects did not omit any statistically significant results, statistical analyses only use the available data and does not factor physical data. Changes in climate, river morphology, and water levels are inconsistent across ten years. The surveying took place throughout three different seasons (spring, summer, and autumn). Despite statistical analysis delivering no significant results, different seasons have different climates, especially in Canada, a diverse climate country. Based on the Environment and Climate Change Canada available climate data, air temperature was the highest during the summer, meanwhile precipitation was higher during both summer and autumn, with autumn having higher extreme daily rainfall (Environment and Climate Change Canada 2026). Furthermore, previous studies have shown that water levels and water temperature are higher in the summer season, meanwhile wind speeds are higher outside of the summer seasons (Huang et al. 2012; Laizé et al. 2017). Likewise, inconsistencies with the number of sampling points taken at different site locations per year adds bias towards the results, favouring site locations with a larger number of samplings. Conversely, the FINS datasets variance at site locations with multiple samples consistently had similar variance values to the overall dataset, biases can still be obtained for site locations with lower variance.

A fourth limitation to this study is the time since a ship has passed. While assisting the FINS surveying team, at two site locations in the Upper St. Lawrence River, Renshaw Island (300 metres from the shipping lane) and Stanley Island (95 metres from the shipping lane), two large ships travelled parallel to the islands. Initially, the water level along the shoreline would decrease as water was pulled towards the ships, fish were observed to be transported by the waves. As both boats passed, a strong release of wave energy crashed towards the site location with zero fish

recorded. The timing a ship passes alongside a surveying location will influence the results of the survey.

A final limitation that will be discussed are the unmeasured ecological variables. Some unmeasurable ecological variables consist of behavioural interactions, food availability, mortality rates, and fish life stages. Behavioural interactions between species will interact differently with each other. Competition between fish for food, mating, and habitat spaces are difficult to measure and manage. Additionally, territorial fish will defend their habitat from other species, influencing the richness and abundance of fish found at site locations. Food availability is a big aspect that determines fish habitats. Habitats with low abundance of food will be less favourable for fish and will encourage them to migrate to stronger nourishment habitats. Rate of mortality is not assessed and higher rates for individual fish species will limit the site locations where fish are found relative to fish species with lower rates. Finally, different stages of life for fish will require different needs. Depending on their life stage, they may need habitats with calmer waters, higher nourishment, or higher oxygen levels.

3.2 Recommendations for Future Work

This research consisted of two main components: (1) field work data provided by the St. Lawrence River Institute, and (2) a statistical data analysis. While I do not have the expertise to comment on the approach that the St. Lawrence River Institute uses for fish surveying, their traditional method (seine) and modern approach (eDNA) method covers the two typical surveying methods. Despite this, other factors in addition to the FINS surveying have been mentioned in previous studies.

However, for additional field work data, based previous research, water depth and current velocities at site locations would be good variables to measure. Rosenfeld (2003) describes microhabitat models predictors at a fine scale usually use water depth and currently velocities. Similarly, Wang et al. (2022) found that physical properties such as water depth and velocity, alongside water quality parameters such as dissolved oxygen and water temperature were strongly correlated with benthic and sub-benthic fish. Additionally, I believe that the steepness of the shoreline would play an impact on the nearshore fish communities due to their effects on waves and the local habitat. My hypotheses for the three variables is the following: (1) deeper site

locations will receive a lower abundance and richness value since deeper water generally has later wave breaking than shallower water, (2) the site locations with higher current velocities will exhibit lower abundance and fish richness due to the higher swimming speed required by smaller fish, similar to the results obtained for exposed site locations in previous studies (Haak et al. 2019), and (3) the steeper shorelines would have a similar result as the water depth as waves would break closer to the shoreline than gradual shorelines where the wave energy would dissipate gradually for gradual shorelines. All three hypotheses can be supported by Goda (2010) who describes that the breaker index for waves (ratio of wave height to water depth) is a function of the bed slope and relative water depth. While these two variables are not the only variables that impact wave breaking, they are still necessary and can be measured in the field. Goda also describes that wave breaking exerts the largest wave action towards structures, causing sediment suspension and morphological changes to the environment (Goda 2010).

Furthermore, field data incorporating direct wake measurements are necessary to further the understanding of wakes at exposed shorelines. Being able to compare the physical differences exerted on exposed shorelines relative to the calmer protected shorelines will further the direct impact on the nearshore ecosystem with respect to average water levels, wave amplitudes, and turbidity along the nearshore ecosystem.

Additionally, the use of automatic identification systems for navigation vessels can provide additional data towards understanding the finer details of vessel movement. The current analyses use buoy locations to determine the shipping lane. While buoys are required for navigation and give a general idea of boundaries for ship movement, using the automatic identification systems allows us to track their movement with higher precision.

Field measurements are crucial to obtain empirical evidence; statistical analyses are just as important to illustrate the importance of the field measurements. There are many recommendations for future work revolving statistics within the FINS database.

The first and most apparent recommendation is to normalize the distribution for fish abundance. As seen in the research article in Chapter 2, the distribution for fish abundance is heavily skewed. As a result, non-parametric testing was performed for the fish abundance analysis while fish richness used ANOVA testing. Normalizing the distribution allows us to pull the skewed

data closer towards the mean (Mendenhall and Sincich 2007), allowing for easier analysis and opens other methods of analyses by having a normal distribution.

The second suggestion to obtain a stronger understanding of the distribution across individual sites would be to average the data between multiple site visits into one data point for that site location (i.e. Thomson Island would have one data point that averages out the six visits). This would allow smoother trends to be observed for the distance to the shipping lane since with multiple visits with the same distance will have variation within the dependent variable, meaning that any variance in the sampling could influence the correlation value. With one average sample point compared to multiple sample points, you lose uniqueness within the values (every visit has different uncontrollable factors (weather, temperature, wind speed, etc.)); however, each site location now has the same amount of weight within the analysis, so site locations with multiple visits do not disproportionate the results with attributes correlated to their particular site location.

The third suggestion I have to obtain stronger results would be to focus on individual sites that have the same characteristics. A comparison of “apples to apples” rather than “apples to oranges”. Isolating a single explanatory variable allows independent contribution with respect to the isolated variable, observing a clearer understanding of the observed variable. In the article in Chapter 2, we showcased this through comparing the exposed shoreline geometries. This allowed us to demonstrate the importance of the shoreline geometry solely towards exposed site locations. Doing this with other variables can enhance the results and influence of different variables. This was attempted with a two way ANOVA method throughout my research; however, every interaction with different combinations of variables did not omit any statistically significant result. However, when I isolated the influence of the shipping lane and solely used exposed site locations, I was able to find a correlation between the shoreline geometry for fish richness. It also provided information about the influence of exposure towards specific shoreline geometries.

Additionally, the use of multivariate ecological analyses could provide a stronger understanding of how multiple variables interact with each other throughout the ecosystem. Understandably, the ecological environments are composed of a variety of different variables where the interactions are not fully understood. Being able to understand the contribution of a variety of these variables will further develop our understanding of the nearshore ecosystem and allow us to isolate the disruptive factors easier.

My final suggestion revolving the statistical analysis consists of the variables within the FINS database that were not observed. As mentioned in Chapter 2, the article talks about other factors in the FINS database that are not covered in the analysis. Two notable variables are water quality parameters (dissolved oxygen, pH, turbidity, and hydraulic conductivity) and the species of fish. The reasoning behind these variables not being covered is because previous research has demonstrated that the physical variables at site locations generally have a stronger influence on the fish communities (Henning et al. 2014; Moustaka et al. 2024; Wang et al. 2022). However, other studies have shown that turbidity plays an important role in fish habitat by reducing the visibility of fish which impacts foraging (Gregory and Northcote 1993; Utne-Palm 2004). Using the turbidity levels found in the FINS database, new observations may be found associating the levels of turbidity with fish abundance and fish richness. Finally, the different species of fish has not be analysed and from previous studies, different species prefer different habitats based on size, habitat composition, life stage, and wave exposure (Depczynski and Bellwood 2005; Henning et al. 2014; Rosenfeld 2003). While this data was not available to me throughout my research, the influence of fish species associated with wave exposure is apparent in previous studies which may correlate with the data available from the FINS database.

Finally, my last suggestion that is outside the scope of field data and statistical analyses involve the use of machine learning. Recently, there has been an uprising in the use of machine learning to further the advancements of our knowledge on ship wake to predict ship wake hydrodynamics through the Reynolds-Average Navier Stokes modelling (Sulovsky et al. 2026). Additionally, ecological articles have outlined that machine learning can provide a flexible resource that allows multiple variables and statistical approaches to occur simultaneously which makes machine learning ideal for ecological problems (Olden et al. 2008).

Implementing these recommendations for future work will assist in our understanding of the navigated vessels towards the nearshore ecosystem and allow us to use that knowledge to provide suitable protection schematics for the benefit of the nearshore fish communities.

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