
Physical, Analytical and Numerical Study of Ship-Generated Waves-Induced Hydrodynamics and Associated Sediment Transport

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Abstract

The Upper St. Lawrence River, a heavily regulated inland waterway connecting the Great Lakes to the Atlantic Ocean, has experienced intensified commercial navigation over the past several decades. This increase in vessel traffic has raised growing concern about the cumulative impact of ship-generated hydrodynamic disturbances—particularly vessel ship-generated waves—on nearshore environments. These disturbances are capable of resuspending bottom sediments, increasing turbidity, and accelerating the degradation of unprotected shorelines. Primary wave components, such as drawdown, and secondary components such as divergent or Kelvin ship-generated waves, can generate high-energy, short-duration events in shallow, sediment-rich areas. Although the ecological and morphological implications of ship-generated waves are widely acknowledged, their specific role in sediment resuspension—especially when isolated from wind-induced forces—remains insufficiently explored in confined, regulated waterways such as the Upper St. Lawrence River.

This research addresses these knowledge gaps through an integrated framework that combines long-term field observations, data-driven modeling, and high-resolution numerical simulations. Two representative nearshore sites—Mariatown and Jacobs Island—were selected based on their contrasting geomorphic features, sediment characteristics, and proximity to the main shipping channel. The sites were monitored for over 300 days using six RBR Duo3 D.TU loggers deployed along shore-normal transects, collecting wave and turbidity data at a 2 Hz sampling frequency. A novel wave separation technique was developed to isolate ship-generated wave signals from overlapping natural waveforms. This approach combined spectral filtering, synthetic Gaussian noise reconstruction of wind and seiche activity, and wavelet-based verification to reliably differentiate anthropogenic from natural forcing events.

Field results showed that secondary ship-generated waves, particularly secondary waves, were responsible for short-lived turbidity spikes up to five times greater than those caused by local wind events. These effects were most pronounced in shallow nearshore zones with fine-grained cohesive sediments and minimal shoreline protection. Spatial variability in turbidity response highlighted the importance of local depth, substrate composition, and logger distance from the navigation channel. By contrast, wind-induced waves produced sustained but lower-intensity turbidity increases, suggesting fundamentally different sediment mobilization mechanisms.

To assess the influence of vessel parameters on wave dynamics and sediment transport, time-delayed multivariate regression and Long Short-Term Memory (LSTM) neural networks were applied. These models incorporated ship-specific inputs—such as speed, draft, length, and hull type—alongside wave and turbidity measurements. Both modeling approaches identified vessel speed and draft as the dominant predictors of wave energy and near-bed shear stress. The results confirmed that fast-moving tankers and cargo ships with deep drafts consistently exceeded shear stress thresholds for erosion, particularly during sequences of closely spaced transits.

In the final phase, a numerical modeling framework was developed by coupling the U.S. Army Corps of Engineers' Vessel Wake Prediction Tool (VWPT) with the DHI MIKE 21/3 Flow Model (FM) modeling suite. A nested large-domain hydrodynamic model was first created to generate boundary conditions based on river-scale flow, wind, and water level data.

This was followed by high-resolution spectral wave and coupled wave-sediment transport simulations at both study sites. The model simulated the propagation of ship-generated waves into the nearshore zone, computed wave orbital velocities and shear stress, and predicted suspended sediment concentration (SSC) and bed-level changes over a synthetic annual time series representing approximately 2,500 ship passages.

Model validation against field data demonstrated strong agreement in spatial wave energy distribution and SSC patterns. Results revealed that energy focusing occurred along concave shoreline segments, resulting in localized erosion and sediment mobilization. However, under current vessel traffic conditions, long-term morphological changes were predicted to be minimal, indicating that ship-generated wave-induced erosion is primarily episodic and site-specific rather than widespread or cumulative at the reach scale.

This novel study contributes a validated, multi-scale framework for quantifying ship wave-induced sediment resuspension in confined inland waterways. The novel wave separation method enhances the classification of hydrodynamic drivers in mixed environments, while the integration of data-driven and numerical modeling provides mechanistic insights into the relationship between vessel traffic and shoreline processes. The findings support the development of evidence-based shoreline protection policies, including speed restrictions, hull design considerations, and localized structural interventions to ensure the sustainable management of navigation corridors subject to increasing anthropogenic pressure.

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List of Symbols

Symbol	Description	SI Unit
B	Ship beam (width)	m
C_D	Drag coefficient	–
C_b	Block coefficient of vessel hull	–
D	Ship draft	m
E	Wave energy density	J/m ²
Fr_L	Length-based Froude number ($U/\sqrt{gL}$)	–
Fr_h	Depth-based Froude number ($U/\sqrt{gh}$)	–
H	Wave height	m
H_b	Bow (near-field) wave height	m
H_m	Maximum cusp-point wave height in divergent-wave system	m
H_s	Significant wave height	m
H_{rms}	Root-mean-square wave height	m
K_w	Empirical coefficient for bow-wave height in Gates–Herbich model	–
L	Characteristic ship length (waterline)	m
L_e	Effective entrance length used in bow-wave formulation	m
L_v	Vessel length used in the Gates–Herbich formulation	m
N	Wave-system index for cusp-point spacing	–
S	Bed slope	–
T	Vessel draft used in VWPT hull coefficients	m
T	Wave period	s
T_p	Peak period	s
T_{peak}	Peak turbidity value used for comparison with τ_w	NTU
U	Ship velocity	m/s
V	Vessel speed (used in some Froude formulations)	m/s
ω	Angular frequency	1/s
ϕ	Angle between return current and wave orbital motion	rad
ρ	Water density	kg/m ³
τ_b	Total bed shear stress	N/m ²
τ_c	Gravitational shear component	N/m ²
τ_w	Wave-induced shear component	N/m ²
f	Frequency	Hz
f_w	Wave friction factor	–
g	Gravitational acceleration	m/s ²
h	Local water depth	m
k	Wavenumber	1/m
u_b	Near-bed orbital velocity	m/s
SSC	Suspended Sediment Concentration	mg/L

List of Acronyms

ADCP Acoustic Doppler Current Profiler.
ADI Alternating Direction Implicit (scheme).
AIS Automatic Identification System.

CFD Computational Fluid Dynamics.
CHS Canadian Hydrographic Service.
CWT Continuous Wavelet Transform.

DFO Department of Fisheries and Oceans (Canada).
DHI Danish Hydraulic Institute.

ECCC Environment and Climate Change Canada.
EMD Empirical Mode Decomposition.

FM Flow Model (DHI MIKE 21/3).
Fr Froude Number.
FT Fourier Transform.

HD-FM Hydrodynamic Flexible Mesh (MIKE 21).
HHT Hilbert–Huang Transform.

IMF Intrinsic Mode Function.

JONSWAP Joint North Sea Wave Project spectrum.

LSTM Long Short-Term Memory (neural network).

NRC National Research Council (Canada).
NRCan Natural Resources Canada.
NSWE Nonlinear Shallow Water Equations.
NTU Nephelometric Turbidity Units.
NWS U.S. National Weather Service.

PSD Power Spectral Density.

RBR Richardson-Bell-Ross (logger manufacturer).
RMS Root-mean-square.

SMS Surface-water Modeling System (mesh generation tool).
SSC Suspended Sediment Concentration.
STFT Short-Time Fourier Transform.
SW Spectral Wave (MIKE 21 SW module).

USACE U.S. Army Corps of Engineers.

VWPT Vessel Wake Prediction Tool.

WPD Wavelet Packet Decomposition.

1 Introduction

1.1 Study Context: The St. Lawrence River

The St. Lawrence River is one of the most prominent and complex freshwater systems in North America, extending from the outflow of Lake Ontario to the Atlantic Ocean via the Gulf of St. Lawrence. It stretches over 1,200 km in total, with approximately 550 km between Lake Ontario and Quebec City forming a navigable freshwater corridor. The river serves as a natural border between Canada and the United States along several segments and drains the Great Lakes Basin, the world’s largest freshwater reservoir, to the Atlantic Ocean [4]. Given its geographic scale and hydrologic connectivity, the St. Lawrence River functions not only as a major conduit for international commerce and transportation but also as a vital ecological and socioeconomic artery.

The river system has historically played a pivotal role in the development of both Canadian and American industrial, agricultural, and urban growth corridors. The completion of the St. Lawrence Seaway in 1959 transformed the waterway into a global trade corridor by allowing ocean-going vessels (lakers and salties) to access inland ports across the Great Lakes. The Seaway, governed collaboratively by the St. Lawrence Seaway Management Corporation (Canada) and the Saint Lawrence Seaway Development Corporation (U.S.), supports the transit of more than 38 million tonnes of bulk, container, and project cargo annually [5]. These commercial volumes underpin critical supply chains in energy, construction, agriculture, and manufacturing sectors [6]. However, the intensity of shipping traffic has raised growing concerns regarding the river’s hydrodynamic and ecological integrity, particularly in confined or shallow nearshore regions where vessel-induced forces can dominate local energy budgets.

Hydrologically, the St. Lawrence River exhibits a strongly regulated flow regime due to extensive upstream reservoir management in the Great Lakes and operational controls at key points such as the Iroquois Dam, which regulates outflow from Lake Ontario, and the Moses-Saunders Power Dam near Cornwall, Ontario. The Moses-Saunders Dam, along with the Beauharnois Hydroelectric Power Station in Quebec, harnesses the river’s flow to generate a substantial portion of renewable energy for eastern Canada and adjacent U.S. states [7]. These hydropower assets are embedded within the larger energy–water–climate nexus of the basin, with their operation influencing seasonal water levels, flow velocities, and sediment transport potential across hundreds of kilometers [7, 8]. In parallel, the river provides drinking water to over 10 million residents in Ontario, Quebec, and New York, emphasizing its role as a public health and infrastructure resource [9].

The ecological importance of the St. Lawrence River is no less profound. It supports a wide range of habitats, from wetlands and floodplains to submerged vegetation beds and rocky nearshore zones, that are critical to the life cycles of numerous aquatic and terrestrial species. The river functions as a major migratory corridor for birds and fish, with several hundred species relying on its diverse ecological niches for breeding, feeding, and staging [10]. These include species of concern under both Canadian and American conservation frameworks. Despite regulatory protections, cumulative pressures from urban development, shoreline modification, thermal and chemical discharges, and vessel-generated wave activity have increasingly altered the ecological balance of sensitive reaches.

From a research perspective, the St. Lawrence River presents a unique natural laboratory for understanding the interaction between anthropogenic drivers and fluvial processes. Although multiple natural and anthropogenic drivers influence the St. Lawrence River, making complete isolation of individual factors challenging, the continuous presence of ship traffic throughout the open-water season provides a strong basis for investigating the influence of vessel-generated waves on sediment resuspension. The high frequency of transits ensures repeated ship-generated wave forcing events, allowing their cumulative effects to be observed and modeled under real operational conditions. Compared to open coastal systems or low-use rivers, the St. Lawrence exhibits a semi-confined geometry, variable bathymetry, and narrow ship corridors, all of which amplify hydrodynamic feedbacks from vessel transits. These conditions make it possible to detect, model, and quantify the impact of ship-generated waves on nearshore sediment transport and morphodynamics with a high degree of spatial and temporal resolution.

Given the growing policy focus on sustainable navigation, shoreline management, and climate resilience across transboundary watersheds [7, 8], there is a pressing need for advanced modeling and empirical observation to inform impact assessments, regulatory thresholds, and mitigation strategies. This research therefore leverages a combination of field-based logger observations, numerical modeling using MIKE 21/3 FM and SW, and synthetic ship passage time series to simulate cumulative effects on wave spectra, suspended sediment concentrations (SSC), and bed level changes across two representative nearshore zones: Mariatown and Jacobs Island.

In this context, the following sections detail the scientific framework, data sources, and modeling strategies employed to evaluate ship-generated wave-sediment interactions under realistic annual vessel schedules. This thesis contributes to the growing body of knowledge on fluvial geomorphology and anthropogenic stressor analysis in regulated large river systems.

1.2 Overview of the Problem

Inland waterways that have been engineered to support large-scale commercial navigation, such as the Upper St. Lawrence River, are experiencing intensifying environmental stress linked to increasing vessel traffic. Among the most significant yet poorly resolved stressors are ship-generated waves, which introduce a distinct set of low-frequency hydrodynamic forces to shallow, nearshore zones. Unlike wind-driven waves that are short-period, multidirectional, and often dissipated by fetch limits, vessel-induced waves—comprising divergent primary waves, drawdown, and return flow—are longer in period and energy persistence, often propagating far beyond the navigation channel into sediment-sensitive margins [11–16].

Despite the increasing awareness of their impacts, several fundamental knowledge gaps remain. First, separating ship-generated wave signatures from ambient wave fields remains an unresolved challenge. In regulated river systems, ambient wind forcing and ship traffic often overlap temporally and spectrally, creating mixed wave climates that obscure signal attribution [17–19]. The irregularity and superposition of wave components result in non-stationary signals that are difficult to decompose using conventional techniques, leading to uncertainties in both observational analysis and subsequent interpretation of impact [11, 20].

Second, the cumulative morphodynamic consequences of sustained ship traffic are still poorly quantified. Existing field studies often rely on short observation windows or physical

experiments that fail to capture the scale and temporal dynamics of year-round commercial operations [21–23]. This is especially critical in inland systems with cohesive sediments, where erosion is governed by nonlinear thresholds of critical shear and water level variability [12]. Few empirical efforts have measured bed level change or sediment resuspension over seasonal or annual periods under real operational conditions.

Third, existing approaches to classify and track ship wave activity often depend on proxy indicators—such as AIS records, camera detection, or visually confirmed passages—that may overlook the role of secondary and reflected wave groups or fail to detect unlogged vessel activity [11, 17, 18]. These approaches provide limited resolution on how vessel type, speed, direction, and draft interact with local bathymetry and shoreline slope to generate sediment-relevant wave energy.

Fourth, there is little general agreement on how to apply oceanographic spectral models to confined riverine settings, where wave directionality is constrained and geometric confinement influences wave convergence, reflection, and shoreline interaction [19]. Many existing studies adopt simplified spectral assumptions that do not account for asymmetric wave exposure or propagation delays introduced by complex channel geometries.

Finally, the absence of high-resolution, long-duration monitoring programs limits the ability to detect changes, isolate anthropogenic wave impacts from natural variability, or validate empirical patterns of shoreline retreat, turbidity fluctuation, or benthic habitat loss [16, 23, 24]. Without real-condition data, the understanding of wave-sediment processes under operational vessel forcing remains fragmented.

These unresolved issues collectively define the research problem addressed in this thesis. Ship-generated waves in inland waterways represent a complex, under-quantified, and poorly isolated class of environmental stressors whose impacts span hydrodynamics, sediment transport, and ecological stability. The absence of empirical separation methods, scalable wave characterization frameworks, and morphodynamic validation under real traffic conditions has hindered both regulatory response and scientific understanding.

Recent efforts have explored advanced signal processing techniques—particularly wavelet transforms—to separate ship-generated hydrodynamic signals from ambient wave noise. Unlike traditional Fourier methods, wavelet-based approaches excel in analyzing nonstationary, multiscale signals due to their simultaneous time-frequency localization, enabling decomposition of transient ship-induced disturbances amidst natural variability [25, 26]. Morlet wavelets have proven especially useful for isolating low-frequency energy signatures characteristic of drawdown and secondary wave fields [27]. Pethiyagoda et al. (2017) extended this approach by applying both frequency-domain and time-frequency analysis to characterize ship-generated waves in shallow water environments, demonstrating that ship-generated wave components exhibit distinctive spectral signatures that can be used for classification and model validation. Their study emphasized the importance of combining wave measurements with theoretical modeling to resolve wave group structures in confined and dispersive settings [28].

However, these methods are typically tested in structured or semi-idealized environments, such as controlled tank experiments, calm coastal bays, or under single-source vessel forcing, with minimal spectral overlap or turbidity signals caused by suspended sediment resuspension from multiple overlapping drivers. Consequently, their performance in highly variable

Table 2 Unresolved Challenges in Quantifying Ship-Induced Effects in Inland Waterways

Challenge	Description and Gap
Wave Signal Overlap	Superposition of wind and ship waves creates spectrally mixed signals that resist decomposition
Limited Duration Field Studies	Short-term campaigns fail to capture seasonal or annual effects of repeated ship traffic
Poor Attribution Accuracy	Automatic Identification System (AIS)-based filters and visual detections may miss secondary energy arrivals or unlogged passages
Directional Constraint Ignored	Models assume broad wave directions inappropriate for narrow channels
Sediment Threshold Ambiguity	In cohesive beds, erosion thresholds vary with shear history and water level often not captured
Lack of Morphodynamic Data	No field programs have measured bed change under real vessel traffic for more than short windows
Spectral Model Calibration Gaps	Spectral assumptions (e.g., Joint North Sea Wave Project spectrum (JONSWAP)) not tailored to river wave climate
Underexplored Return Flow and Drawdown	Long-period secondary flows often excluded or misclassified in energy budgets
Neglect of Reflection Effects	Reflected waves compound exposure near shorelines in narrow rivers but are rarely mapped
No Cross-Disciplinary Integration	Most studies isolate hydrodynamics, sediment, or ecology rarely linking them under real-world forcing

inland systems with mixed wind–ship forcing, high sediment load, and shoreline reflection remains largely untested.

Furthermore, while wavelet denoising enhances temporal isolation, most studies do not integrate environmental validation metrics such as turbidity spikes, suspended sediment concentration, or benthic shear thresholds. Without this, the inferred sedimentary impact remains hypothetical. Comparative studies evaluating the relative effectiveness of wavelet, Fourier, and hybrid machine learning methods in real, sediment-rich inland settings remain virtually absent, highlighting a critical research gap.

1.3 Research Objectives, Novelty, and Contributions

This thesis addresses the complex dynamics of ship-generated waves in regulated inland waterways and their influence on sediment resuspension, deposition, and shoreline integrity. Building on an integrated research approach that combines high-frequency field data, spectral analysis, and process-based modeling, the primary objective of this work is to isolate, quantify, and predict the impacts of commercial vessel activity on nearshore sediment dynamics in the Upper St. Lawrence River.

The overarching research objective is to evaluate the generation, propagation, and sedimentary effects of ship-induced wave fields—distinct from wind-driven or ambient hydrodynamic forces—using a combination of empirical and numerical techniques tailored to confined freshwater systems.

To achieve this, the research is structured around four specific objectives:

1. To develop and validate a hybrid signal separation framework for distinguishing natural wind wave activity from ship-generated wave signals in mixed-forcing river environments. The approach combines spectral analysis techniques with a time-domain thresholding

algorithm applied to surface elevation records, where synthetic Gaussian noise is superimposed to simulate background wind wave variability. The method enables both (1) separation of ship-induced signals from natural waveforms, and (2) decomposition of ship waves into primary (drawdown) and secondary (divergent) components. Event validation is performed using synchronized Automatic Identification System (AIS) vessel tracks and logger observations.

2. Field-based quantification of ship-induced turbidity and near-bed stress: Collect and analyze high-resolution depth and turbidity data at two nearshore locations, Mariatown and Jacobs Island, using bed-mounted loggers. Evaluate how ship characteristics (speed, draft, length, hull geometry) influence sediment resuspension, turbidity, and near-bed shear stress.
3. Numerical modeling of ship wave-sediment interactions: Simulate one year of synthetic ship traffic using the Vessel Wake Prediction Tool (VWPT) and DHI's MIKE 21 SW and 21/3 FM modules to evaluate ship-generated wave effects on sediment suspension and deposition. Models were configured to isolate ship impacts by excluding natural wind and current forcing.
4. Model validation and integration with real-world monitoring: Validate model predictions using logger-based turbidity time series, SSC conversion functions, and shoreline erosion markers (e.g., physical erosion rods) to establish direct correspondence between simulated and observed sediment response.

Following these objectives, the key novelties of this research are summarized below.

- This thesis introduces a method in which synthetic Gaussian noise is used to emulate background wind-wave variability, enabling reliable isolation of natural versus ship-generated waves and subsequent decomposition of ship-induced signals into primary (drawdown) and secondary (divergent) components.
- This research develops a unified framework linking high-frequency field observations, time-lagged multivariate regression, LSTM neural networks, the Vessel Wake Prediction Tool (VWPT), and MIKE 21 SW / MIKE 21/3 FM simulations to quantify ship-wave forcing and sediment response under real operational navigation conditions.

This research advances current knowledge through several key contributions:

- This thesis introduces a signal spectral analysis framework for overlapped irregular waves, in which Gaussian noise is used to simulate background natural wave during ship-passage events. This approach enables the separation of natural and ship-generated wave components, followed by decomposition of primary and secondary ship-wave signals, which are subsequently validated using wavelet analysis.
- It applies a multi-variant time-delayed regression model to quantify the individual and combined influences of ship speed, draft, and vessel class on wave height, orbital velocity, and suspended sediment concentration (SSC), providing the first such field-based analysis in the Upper St. Lawrence River.
- Building on this, it integrates logger-based turbidity data, turbidity-to-SSC conversion models, and Long Short-Term Memory (LSTM) neural networks into a predictive framework, representing a novel application of machine learning to forecasting sediment resuspension risk under variable shipping conditions.

- It constructs a synthetic annual time series of wave forcing representing approximately 2,500 vessel passages, compressed into about 250,000 model steps, enabling one-year simulations of erosion, resuspension, and deposition that extend beyond the short-term focus of most prior studies.
- It establishes an integrated field-to-model framework coupling logger observations, the Vessel Wake Prediction Tool (VWPT), and MIKE 21/3 FM simulations. By excluding wind and ambient current forcing in the high-resolution domains, this framework isolates the contribution of vessel traffic to sediment dynamics under real operational conditions.
- Finally, it validates numerical predictions against direct field evidence from erosion rod surveys and SSC measurements.

Together, the three papers offer a multi-tiered framework, from signal decomposition and field analysis to high-resolution wave–sediment modeling, for understanding vessel-induced sediment dynamics under operational navigation conditions. The findings contribute directly to sustainable shoreline management, navigation policy, and sediment risk mitigation in large regulated rivers.

1.4 Thesis Outline and Organization

This dissertation is presented in a manuscript-based format and consists of three journal articles that collectively investigate ship-generated wave processes and their effects on sediment dynamics in the Upper St. Lawrence River. The structure follows a progressive sequence, from field-based signal decomposition to high-resolution numerical modeling. Although each manuscript is designed to be self-contained, the chapters are interrelated and contribute to a unified research framework. The organization of the thesis is as follows:

- **Chapter 1** introduces the study context, outlines existing knowledge gaps, and defines the central research problem. It presents the overarching research objectives, novel contributions, and structure of the thesis.
- **Chapter 2** provides a comprehensive review of relevant literature on ship-generated wave dynamics, spectral wave decomposition methods, wave–current–sediment interactions in inland waterways, and cohesive sediment transport under unsteady forcing. It also discusses numerical modeling tools and in-situ measurement techniques used in the field of sediment transport and wave analysis.
- **Chapter 3** details the unified methodology employed across all three studies. It describes the study sites, instrumentation setup, signal processing approach for wave separation, development of synthetic forcing time series, and the setup of numerical models (MIKE 21 SW, FM, and sediment transport modules). Key assumptions, boundary conditions, mesh generation, validation strategies, and simulation configurations are presented to ensure reproducibility and clarity across the research framework.
- **Chapter 4** (Paper I) presents a signal separation framework to isolate ship-generated wave signals from overlapping wind wave activity in field-recorded time series. Using a combination of frequency-domain spectral analysis and slope-based detection thresholds applied to surface elevation data augmented with Gaussian-simulated natural wave noise, the method successfully distinguishes primary (drawdown) and secondary (divergent) ship wave components. Ship passages are validated using AIS-derived trajectories, and the

extracted events are cross-checked against high-resolution logger observations at two study sites.

- **Chapter 5** (Paper II) expands the observational analysis to assess the spatial and temporal variability of ship wave forcing and sediment response at two nearshore locations—Jacobs Island and Mariatown. Differences in shoreline exposure, bathymetry, and vessel traffic are evaluated using co-located wave and turbidity loggers. The study quantifies wave height thresholds associated with elevated turbidity, highlights event clustering patterns, and identifies how local morphology influences nearshore sediment mobilization under real-world navigation conditions.
- **Chapter 6** (Paper III) develops and applies an integrated numerical modeling framework using MIKE 21 Spectral Wave (SW) and Flow Model (FM) modules, coupled with a cohesive sediment transport model. The model simulates isolated impacts of ship-generated wave forcing on suspended sediment concentration (SSC) and bed level change at both study sites. A synthetic time series representing 2,500 ship passages over one year, derived from VWPT simulations and applied via JONSWAP spectral boundary conditions, is used to force the model. Wind waves and wind-induced currents are excluded to isolate the contribution of ship waves alone. Model predictions are validated against logger-based SSC measurements and field-observed morphological trends.
- **Chapter 7** synthesizes the findings across all three papers, emphasizing the implications for sediment management, shoreline protection, and inland navigation policy. It outlines methodological limitations and proposes a roadmap for future research. This includes an ongoing research initiative funded by Environment and Climate Change Canada (ECCC), which will extend the modeling framework to address long-term shoreline erosion under evolving climate and navigation scenarios.

1.5 Publications

Lists the publications and manuscripts associated with this dissertation. It includes all peer-reviewed articles accepted or submitted during the course of the PhD:

1. Haghighi, A., Rennie, C., Nistor, I.: Ship-generated wave-induced sediment dynamics in Upper St. Lawrence River: Analysis of field data. *Natural Hazards* (2025). <https://doi.org/10.1007/s11069-025-07445-3>, **Chapter 4**
2. Haghighi, A., Nistor, I., Rennie, C.: Impact of Ship Characteristics on Wave Dynamics and Sediment Resuspension in the Upper St. Lawrence River: A Field Data Analysis. Manuscript is in review at ASCE-JWPCOE (2025), **Chapter 5**
3. Haghighi, A., Rennie, C., Nistor, I.: Integrated Numerical Modeling of Ship-Generated Wave-Induced Hydrodynamics and Sediment Resuspension in the Upper St. Lawrence River. Manuscript is ready for submission (2025). **Chapter 6**

2 Background and Literature Review

2.1 Ship-Generated Wave Theory and Dynamics

Large commercial vessels operating in regulated inland waterways generate a distinct class of hydrodynamic disturbances that differ significantly in both structure and persistence from wind waves or natural fluvial flows. These disturbances, comprising ship-generated wave, and return flow, can propagate laterally well beyond the navigation channel and influence sediment-sensitive riverbanks. Unlike deep-ocean or coastal wave regimes, inland ship waves evolve under constrained geometries, complex boundary reflections, and frequent vessel traffic, presenting unique challenges for quantifying their dynamics and potential sediment impacts.

Ship-generated waves in rivers are commonly categorized as: (i) primary waves, often manifested as long-period drawdown; (ii) secondary waves, consisting of divergent and transverse wave trains; and (iii) return flows, which represent the nearshore compensatory currents induced by drawdown [29, 30]. Figure 1 illustrates the initial wave patterns generated by the movement of a vessel, providing a visual foundation for understanding the primary and secondary components of ship-generated waves.

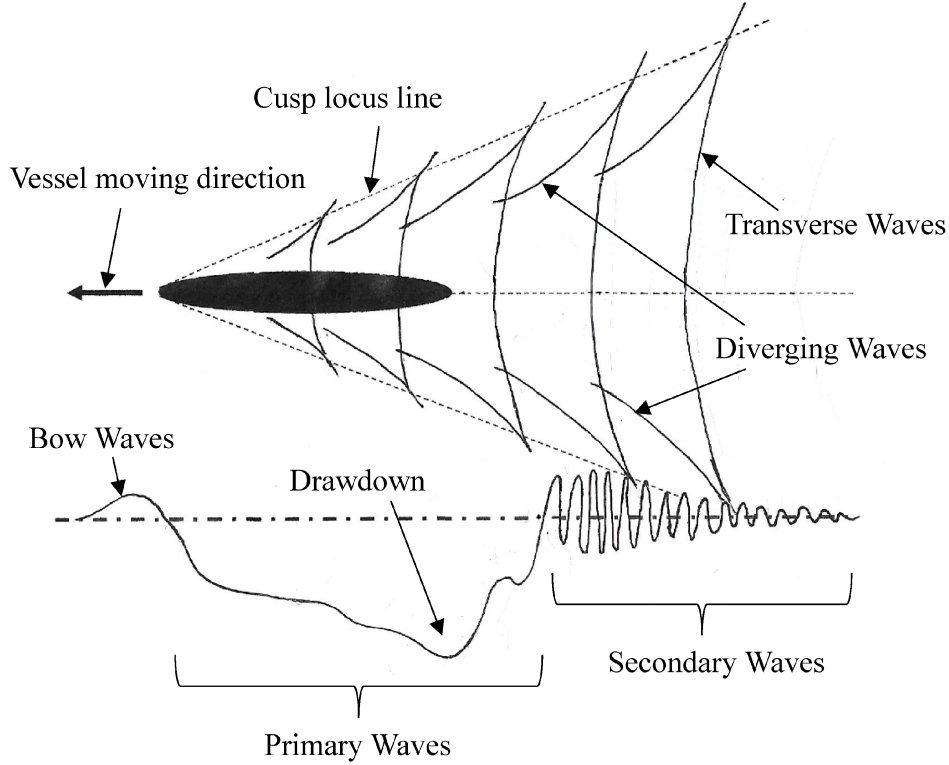


Fig. 1 Typical wave patterns generated by a moving vessel [1].

The following table presents a comparison of the characteristics of primary and secondary ship-generated wave components and their respective impacts on turbidity. It summarizes key dynamics including the influence of the Froude number, wave frequency and wavelength, and wave height, based on previous work by Dempwolff et al. [31], Rabaud and Moisy [32], Soomere [33], Garel et al. [34], and Bilkovic et al. [35]. This comparison illustrates how different ship-generated wave types affect sediment resuspension, water clarity, and energy distribution in riverine environments.

Table 3 Comparative Analysis of Ship-Generated Wave Characteristics and Their Effects on Turbidity

Aspect	Primary Waves	Secondary Waves
Froude Number Effect	Significantly impacts wave amplitude and energy propagation. In subcritical regime ($Fr_h < 1$), results in larger, more elongated waves.	Dictates the spreading angle and wave intensity. As Fr_h approaches or exceeds unity ($Fr_h \geq 1$), the ship-generated wave narrows, concentrating wave energy.
Frequency and Wavelength	Low-frequency, long-wavelength waves influence large areas, causing significant but gradual impacts.	Higher frequency, short-wavelength waves produce more localized but intense interactions.
Wave Height	Often exhibit greater individual wave heights due to hull displacement and drawdown effects.	Can show cumulative height effects from interference and focusing, especially in confined or shallow channels.
Impact on Turbidity	Cause significant sediment resuspension and turbidity spikes through slow, large-scale disturbance events.	Promote downstream transport of suspended sediments, shaping turbidity plumes and dispersal patterns.

In confined rivers, drawdown leads to rapid shoreline water level decline, followed by return flow surges that can generate horizontal shear stress near the bed. Secondary waves, typically higher in frequency, exhibit directional spreading that interacts with shoreline slope and bathymetry [36, 37].

Wave regimes are characterized by the depth-based Froude number:

$$Fr_h = \frac{U}{\sqrt{gh}}, \quad (1)$$

where U is ship velocity, g is gravitational acceleration, and h is local water depth. Subcritical flow conditions ($Fr_h < 1$) dominate most inland waterways, yielding both drawdown and transverse waves. Near-critical flow ($Fr_h \approx 1$) can amplify ship-generated wave energy and steepness [33]. The length-based Froude number:

$$Fr_L = \frac{U}{\sqrt{gL}}, \quad (2)$$

where U is ship velocity (m/s), g is gravitational acceleration (9.81 m/s²), and L is the characteristic ship length (m), typically taken as the waterline length. The length-based Froude number (Fr_L) is also useful for estimating ship-generated wave angles and wave

dispersion characteristics. Additional influencing factors include hull block coefficient, vessel beam-to-draft ratio, and the width-to-depth ratio of the navigation channel [38].

Wave propagation in rivers is strongly influenced by channel confinement, bathymetric discontinuities, and boundary reflections. While the classical shallow water dispersion relation:

$$\omega^2 = ghk^2, \quad (3)$$

where, ω is the angular frequency of the wave (rad/s), g is gravitational acceleration (9.81 m/s²), h is the local water depth (m), and k is the wavenumber (rad/m), is often assumed, real-world riverine conditions introduce substantial nonlinearity [39]. Armored or steep banks amplify energy through reflection and interference, particularly when wave groups arrive at oblique angles [31, 37]. Field studies in confined waterways have demonstrated that reflected drawdown and trailing return flows can persist for several minutes, sustaining nearshore shear and increasing the likelihood of sediment resuspension [36].

Even in low-flow, windless conditions, vessel-induced wave forcing can generate sufficient shear stress to resuspend fine-grained sediments. Total bed shear stress is approximated as:

$$\tau_b \approx \rho ghS + \rho C_D U^2, \quad (4)$$

where ρ is water density, S is bed slope, C_D is drag coefficient, and U is wave-induced near-bed velocity. The first term represents gravitational forcing; the second captures dynamic effects from return flow and ship-generated wave interaction.

Gravitational Component

$$\tau_c = \rho ghS \quad (5)$$

This follows the classical depth-slope product used in open-channel hydraulics [40, 41].

Dynamic Component

$$\tau_w = \frac{1}{2} \rho f_w U^2 \quad (6)$$

This quadratic law is widely applied in wave-current bottom boundary layers [42, 43].

Theoretical Combined Formulation

$$\tau_b = \sqrt{\tau_c^2 + \tau_w^2 + 2\tau_c\tau_w \cos \phi}, \quad (7)$$

where ϕ is the angle between return current and wave orbital motion [43–45].

This thesis models ship wave-induced shear fields and simulates resulting sediment suspension and deposition patterns under low ambient current. Results indicate that even isolated passages can exceed entrainment thresholds and trigger short-lived, localized turbidity pulses and resuspension. These effects are most pronounced during the return flow phase or at drawdown troughs, and their outcomes depend on local geometry, wave duration, and sediment cohesion.

While wave propagation theory is well-developed for coastal settings, riverine environments present unresolved challenges:

- **Mixed-forcing attribution:** Separating ship-generated signals (primary drawdown, secondary wakes, return flows, reflections) from overlapping wind and seiche energy in nonstationary, spectrally mixed records.

- **Short monitoring windows:** A lack of long-duration, high-frequency observations that capture seasonal/annual traffic patterns and their cumulative sediment impacts.
- **Vessel-to-response linkage:** Poor resolution of how ship parameters (speed, draft, length, hull) interact with local bathymetry and shoreline slope to produce sediment-relevant wave energy.
- **Confinement and reflection:** Directional constraints and geometric confinement in regulated channels leading to wave convergence, persistent drawdown/return flows, and reflection, rarely mapped or quantified in river settings (e.g.,[46–48]).
- **Cohesive-bed thresholds:** Ambiguity in critical shear for cohesive sediments under short, high-intensity events and variable water levels, hindering prediction of turbidity pulses and resuspension.
- **Model–field gap:** Spectral and process models adapted from coastal practice that lack validation against turbidity/SSC and bed-change observations.
- **Low-background-flow regimes:** Weak nearshore currents that limit advective dispersion, allowing brief ship events to dominate near-bed shear and sediment response.

Numerical tools such as MIKE 21 or MIKE 21/3 offer wave simulation capacity but often lack sediment feedbacks or reflection-aware boundary handling. Furthermore, most existing models do not integrate turbidity metrics, sediment concentration, or deposition data as validation, limiting ecological and morphodynamic inferences.

In contrast, this thesis isolates ship-generated effects from ambient influences and evaluates short-term sediment responses in field-calibrated settings. While long-term erosional dynamics modeling was limited to one year of event-scale simulations, the results provide insight into the initiation of sediment mobility through hydrodynamic forcing alone.

Ship-generated wave groups in narrow inland waterways can introduce drawdown, secondary waves, and return flows that generate localized shear and disturb sediment beds, even under low-wind, low-current conditions. Although such events may not always cause measurable erosion, they can produce short-term suspension and deposition cycles that cumulatively affect nearshore conditions. A variety of empirical and modeling studies have examined similar effects across riverine and lagoonal systems. These are summarized in Table 4, which highlights foundational and contemporary work relevant to ship-generated wave dynamics and sediment response.

2.2 Signal Decomposition and Wave Separation

Accurately separating ship-generated wave signals from ambient natural variability (e.g., wind waves, background turbulence) remains a critical step for quantifying hydrodynamic and sedimentary impacts in confined waterways. Traditional signal decomposition techniques based on Fourier transforms assume stationarity and global periodicity [36], which poorly suit the transient, multi-scale nature of vessel-induced waves. More recent efforts have turned to wavelet-based and hybrid methods to isolate primary drawdown, secondary waves, and precursor oscillations from complex field data.

The Fourier Transform (FT) decomposes a signal into sinusoidal components across frequency and is defined for a continuous-time signal $x(t)$ as:

Table 4 Key Studies on Ship-Generated Wave-Induced Shoreline and Sediment Impacts

Citation	Description
Sorensen (1973) [49]	Early empirical study quantifying boat wave heights and energy decay in shallow waters
Zabawa and Ostrom (1980) [50]	Investigated boat wave characteristics and their influence on shoreline erosion in Chesapeake Bay
U.S. Army Corps of Engineers (1994)	Technical report on boat wake impacts and mitigation strategies in navigable waters
Nanson et al. (1994) [51]	Experimental field study quantifying river-bank erosion from boat-generated waves on the Gordon River (Tasmania), among the earliest systematic measurements of direct wake-induced erosion
Asplund (1996) [52]	Examined impacts of boat wakes on water clarity and sediment resuspension in lakes
Bauer et al. (2002) [53]	Analyzed the relationship between vessel speed, wave energy, and bank retreat in river channels
Parnell et al. (2007) [54]	Studied high-speed ferry wake impacts on sensitive shorelines in Marlborough Sounds, New Zealand
Houser (2010) [55]	Compared relative importance of vessel-generated vs. wind waves for salt marsh erosion in restricted fetch environments, showing vessel wakes can dominate erosion processes
Fonseca and Malhotra (2012) [56]	Developed semi-empirical models to predict wake wave heights from vessel properties
Tezdogan et al. (2016) [57]	Applied CFD simulations to model ship-generated wave propagation and erosion potential near banks
Zaggia et al. (2017) [23]	Quantified wake-induced sediment erosion and turbidity in the Venice Lagoon using field sensors
Duro et al. (2020) [58]	Investigated bank erosion in the Meuse River from repeated wake exposure using long-term shoreline monitoring
Muscalus and Haas (2022) [59]	Used field sensors to quantify turbidity pulses and erosive stress from ship-generated waves in the Savannah River
Chakraborty et al. (2024) [60]	Demonstrated high-frequency turbidity events linked to vessel wakes in Restricted Waterways

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-2\pi ift} dt, \quad (8)$$

where f is the frequency and i is the imaginary unit. While analytically robust, FT assumes signal stationarity and cannot resolve time-localized events. The Short-Time Fourier Transform (STFT) attempts to add time resolution by applying a moving window function:

$$STFT_x(t, f) = \int_{-\infty}^{\infty} x(\tau)w(\tau - t)e^{-2\pi if\tau} d\tau, \quad (9)$$

where $w(t)$ is a fixed-size window [61]. However, STFT suffers from a fundamental trade-off between time and frequency resolution due to the Heisenberg uncertainty principle, making it unsuitable for detecting both long-period drawdown and short-period wake signals simultaneously.

In dynamic riverine environments, overlapping spectral energy from multiple vessels, wind waves, and reflections causes FT-based methods to underperform. Ship-generated wave

signals may be smeared across frequency bands or misclassified, particularly in narrow, high-traffic rivers where confinement intensifies wave reflection and mixing [30].

Wavelet transforms offer improved localization in both time and frequency domains. The Continuous Wavelet Transform (CWT) of a signal $x(t)$ is given by:

$$W(a, b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t) \psi^* \left(\frac{t - b}{a} \right) dt, \quad (10)$$

where $\psi(t)$ is the mother wavelet, a is the scale parameter (inverse to frequency), b is the time-shift, and $*$ denotes the complex conjugate [25, 62]. Wavelet Packet Decomposition (WPD) extends this to decompose both low- and high-frequency components recursively.

This framework has been used to decompose primary drawdown, secondary waves, trailing return flows, and reflected signals in riverine field data, where signal nonstationarity is pronounced [25].

However, wavelet transforms assume that signal components are separable in time–frequency space. In field conditions with high spectral overlap—such as simultaneous ship passages, wind forcing, and shoreline reflections—components with similar frequency but different physical origins may become indistinguishable. This results in mode mixing, where wavelet coefficients capture multiple sources and thereby reduce interpretability [63]. In addition, the performance of wavelet transforms depends strongly on the selection of the mother wavelet (e.g., Morlet), which is typically heuristic and problem-specific.

Empirical Mode Decomposition (EMD) offers a data-adaptive alternative by decomposing signals into Intrinsic Mode Functions (IMFs) without requiring predefined basis functions. While more flexible than wavelets for nonlinear and nonstationary signals, EMD is sensitive to noise and vulnerable to mode leakage. The Hilbert–Huang Transform (HHT), which applies the Hilbert transform to EMD-derived IMFs, enables the extraction of instantaneous frequency, a property particularly useful for wave trains with irregular energy dispersion [63].

The method-specific strengths and weaknesses are summarized in Table 5, which highlights the current state of signal decomposition strategies in ship-generated wave studies.

Wavelet-based techniques remain powerful for nonstationary signal analysis, but their effectiveness declines under overlapping forcing typical of field conditions. Adaptive approaches such as EMD and HHT show promise for resolving irregular and nonlinear dynamics, yet none currently provide reliable decomposition in sediment-rich, real-world environments without empirical validation. Comparative performance studies and integration with environmental indicators (e.g., turbidity, SSC) are urgently needed to advance signal separation in ship-wave research.

2.3 Numerical Modeling of Ship-Generated Waves in Confined Waterways

Understanding and predicting the dynamics of ship-generated waves in inland and confined waterways is critical for evaluating their impact on sediment transport, bank stability, and overall hydraulic behavior. Unlike open sea environments, rivers and canals are characterized by limited spatial scales, complex boundaries, and low-energy ambient conditions, making wave propagation highly sensitive to vessel-induced disturbances. To address these challenges, a variety of numerical models have been developed, ranging from simplified linear

Table 5 Comparison of signal decomposition methods for ship wave separation.

Method	Strengths	Limitations	Best Use Case
Fourier Transform	Frequency decomposition for stationary signals; well established	No time resolution; unsuitable for nonstationary or transient events	Long-term averages; low-noise environments
Short-Time Fourier Transform (STFT)	Adds time resolution via windowing	Fixed window restricts frequency–time localization; weak for multi-scale events	Signals with limited temporal variability
Wavelet Transform (CWT, WPD)	Multiscale, nonstationary decomposition; good time–frequency localization	Overlap of sources at similar frequencies leads to mode mixing; mother wavelet choice is heuristic	Ship waves and return flows with distinct, separable signatures
Empirical Mode Decomposition (EMD)	Adaptive, data-driven; no basis needed; effective for nonlinear, nonstationary data	Sensitive to noise; prone to mode splitting (leakage)	Highly irregular, overlapping field signals
Hilbert–Huang Transform (HHT)	Provides instantaneous frequency from IMFs; captures transient bursts	Dependent on EMD stability; limited validation in field applications	Nonlinear energy shifts, sediment–wave interactions
Wavelet + Machine Learning	Enables pattern recognition and vessel classification; robust automation	Requires training data; limited interpretability; risk of overfitting	Automated detection under well-defined signal windows

wave theory to fully resolved Navier-Stokes solvers, each with distinct capabilities and limitations. This section presents a comprehensive technical overview of the governing equations, modeling tools, and theoretical foundations relevant to simulating ship-generated wave phenomena. Emphasis is placed on models and equations applicable to shallow water settings with low ambient flow, as aligned with the scope of this thesis. The discussion also provides a critical review of existing software such as MIKE 21/3, USACE’s VWPT, and hybrid approaches, setting the groundwork for the selection and justification of modeling strategies in subsequent chapters.

Ship-generated waves in inland and riverine environments are governed by complex hydrodynamic processes influenced by confined geometries, shallow depths, and reflective boundaries. Accurate numerical simulation of these wave fields is critical for understanding their impacts on sediment dynamics, bank erosion, and infrastructure loading. Due to the impracticality of extensive field experiments, numerical models offer a cost-effective and replicable means to simulate wave generation, propagation, and interaction.

A hierarchy of modeling approaches is employed, each with specific assumptions, computational demands, and levels of fidelity [64, 65]. These range from linear wave theory to computational fluid dynamics (CFD), depending on the desired resolution and available resources.

The simplest representation is linear (Airy) wave theory, which assumes inviscid, incompressible, and irrotational flow [66]. It is most suitable for deep water and small-amplitude

waves, governed by Laplace's equation and leading to the dispersion relation:

$$\omega^2 = gk \tanh(kh), \quad (11)$$

where ω is the angular frequency [s^{-1}], k is the wave number [m^{-1}], h is the water depth [m], and g is gravitational acceleration [m/s^2]. While analytically convenient, linear theory fails to capture the nonlinear and dispersive effects dominant in shallow and narrow waterways. Nevertheless, it underpins phase-averaged spectral wave models such as MIKE 21 SW, which solve the wave action balance equation for energy propagation in deep- and intermediate-water conditions [67].

To account for nonlinearities and depth dependence, the Nonlinear Shallow Water Equations (NSWE) are used, conserving mass and momentum under the hydrostatic assumption [68]:

$$\frac{\partial \eta}{\partial t} + \frac{\partial((h + \eta)u)}{\partial x} + \frac{\partial((h + \eta)v)}{\partial y} = 0, \quad (12)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial \eta}{\partial x}, \quad (13)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -g \frac{\partial \eta}{\partial y}, \quad (14)$$

where η is the free surface elevation [m], h the still water depth [m], and u, v the depth-averaged velocities [m/s]. These equations are widely applied in MIKE 21 HD, which employs a finite-difference scheme and an Alternating Direction Implicit (ADI) solver for coastal and riverine hydrodynamics [69].

For a more accurate depiction of nonlinear and dispersive processes in intermediate depths, Boussinesq-type equations are employed [70, 71]. A representative form includes higher-order terms that extend linear theory:

$$\frac{\partial \phi}{\partial t} + c \frac{\partial \phi}{\partial x} + \frac{1}{2} c \left(\frac{\partial \phi}{\partial x} \right)^2 + \frac{1}{6} c \frac{\partial^3 \phi}{\partial x^3} = 0, \quad (15)$$

where ϕ is the velocity potential [m^2/s], c is the wave celerity [m/s], x the horizontal coordinate [m], and t time [s]. Boussinesq models are particularly effective for simulating primary (drawdown and diverging) and secondary (dispersive) ship-generated waves. Their balance between physical realism and computational efficiency makes them well suited for inland and semi-enclosed waters, with enhanced formulations implemented in MIKE 21 BW [67]. Numerous studies have demonstrated their strength: Dabbi et al. [72] coupled slender-body theory with Boussinesq equations to simulate ship waves in channels; Shi et al. [73] used adaptive meshing to study ship-induced erosion; Samaras and Karambas [74] applied 2DH post-Boussinesq models to irregular basins; Walkley [75] and Williams [76] introduced higher-order formulations; and Figlus et al. [77] highlighted spatial variability of ship-wave energy in shallow bays. Despite these advances, Boussinesq models still assume weak non-linearity and may underperform under steep wave fronts or near-field phenomena such as wave breaking, reflection, and turbulence.

To resolve three-dimensional turbulent structures near ships (e.g., bow and stern vortices, propeller wash), the incompressible Reynolds-Averaged Navier–Stokes (RANS) equations are employed [78]:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right), \quad (16)$$

and similarly for the v and w momentum components, where u, v, w are the velocity components [m/s], p is pressure [Pa], ρ fluid density [kg/m³], and ν kinematic viscosity [m²/s]. These form the basis of the MIKE 3 Flow Model, which captures near-ship turbulence and vertical velocity gradients with high spatial accuracy [79]. While highly accurate, CFD methods are computationally expensive and generally reserved for localized domains.

Finally, analytical solutions using Green’s functions are occasionally used for model verification. The free-surface Green’s function for ship-generated waves is expressed as:

$$G(x, y, t) = \frac{1}{2\pi r} \exp(-ikr) \exp(-i\omega t), \quad (17)$$

where x, y are spatial coordinates [m], t is time [s], $r = \sqrt{x^2 + y^2}$ is radial distance [m], k the wavenumber [1/m], and ω the angular frequency [rad/s]. Although valuable for theoretical validation, these assume linearity and homogeneity and are therefore limited in real-world riverine applications with variable bathymetry [80, 81].

The choice of wave simulation model depends on site-specific requirements, including domain size, wave nonlinearity, and resolution needs. NSWE and Boussinesq models are effective for broad inland wave assessments, while CFD is necessary for near-field flow fidelity. Emerging best practice recommends hybrid modeling, combining coarse-resolution models for domain-scale flow with localized high-fidelity CFD near vessels, ensuring both accuracy and computational feasibility.

2.4 Sediment Transport and Wave–Sediment Interactions

Sediment transport in riverine and inland environments subjected to ship-generated waves is driven by a combination of bed shear stress, turbulence, wave–current interactions, and site-specific hydrodynamic conditions. While natural background currents in these systems are often too weak to induce significant sediment resuspension, the passage of vessels introduces energetic disturbances that temporarily exceed the critical shear stress thresholds required for sediment entrainment. This section reviews the governing mechanisms of sediment suspension and deposition under the influence of both primary and secondary ship waves, with a particular focus on confined waterways where drawdown effects and low-flow conditions dominate.

Ship-generated waves consist of two main components: the low-frequency, long-period primary wave (drawdown and return wave) and higher-frequency secondary waves caused by the vessel hull and propulsion system [49]. The drawdown represents a negative surface elevation wave generated at the bow, followed by a return wave at the stern. This sudden displacement causes rapid changes in water level and pressure gradients, resulting in temporary but intense near-bed velocities and shear stress [46, 82].

The bed shear stress induced by wave motion is typically expressed as:

$$\tau_b = \rho C_d u_b^2 \quad (18)$$

where τ_b is the instantaneous bed shear stress [Pa], ρ is the fluid density [kg/m³], C_d is the drag coefficient (typically 0.002–0.004), and u_b is the near-bed velocity [m/s] [83]. Field observations in the Göta Älv River and Venice Lagoon report that drawdown events can produce peak shear stresses between 0.3 and 1.5 Pa—values capable of entraining fine and even medium sands, well above typical background levels [29, 84].

The duration of primary wave impact is usually short (several seconds), but it introduces an abrupt pressure gradient and reversal in flow direction, producing a high-intensity but short-lived suspension spike. This leads to rapid entrainment of bed material, particularly from shoals, levees, and banks, where wave breaking and reflection amplify the effect [53]. In contrast, secondary waves, though lower in energy, tend to persist longer and propagate further across the channel. They can maintain elevated shear stress and turbulence for extended periods (minutes), enhancing horizontal advection and diffusive transport of previously resuspended particles [85].

The initiation of sediment motion depends on whether the wave-induced shear stress exceeds the critical shear stress τ_c for sediment mobilization, given by the Shields equation:

$$\tau_c = \theta_c (\rho_s - \rho) g d \quad (19)$$

where θ_c is the critical Shields parameter (typically 0.03–0.06 for non-cohesive sand), ρ_s is sediment density [kg/m³], d is median grain size [m], and g is gravitational acceleration [m/s²] [86, 87]. Both field and flume studies have demonstrated that even brief ship-induced wave events can surpass this threshold, triggering localized suspension of sediment layers that would otherwise remain stable under ambient flow conditions [29, 60].

In systems with low background currents, this entrained material may not be transported far from the source. Instead, as the wave-induced shear stress diminishes, rapid deposition occurs within meters of the resuspension site, leading to repetitive erosion–deposition cycles in the same locations. This explains observed zones of persistent turbidity and elevated sedimentation near shipping lanes and turning basins [29, 88].

The vertical distribution of suspended sediment can be described using the Rouse profile:

$$C(z) = C_a \left(\frac{h-z}{z} \right)^R, \quad R = \frac{w_s}{\kappa u_*} \quad (20)$$

where $C(z)$ is the sediment concentration at height z , C_a is the reference concentration near the bed, h is total depth, w_s is the settling velocity [m/s], $\kappa \approx 0.4$ is the von Kármán constant, and u_* is the shear velocity [89–91]. In low-flow environments, u_* is minimal outside ship passages, leading to steep Rouse profiles and near-bed stratification, which favors redeposition.

Besides surface wave action, propeller jets and secondary circulations also play crucial roles in sediment dynamics. Propeller-induced scouring can resuspend fine and coarse sediments, generating localized vortices that entrain particles well above the bed [92]. These hydrodynamic structures interact with vessel-induced currents and bedform features, enhancing lateral dispersion and vertical mixing of sediments, particularly in confined areas such as harbors, turning basins, and locks.

Drawdown events cause rapid water level drops (sometimes exceeding 0.5 m) over several seconds, generating a pressure-driven horizontal flow along the bed. This flow can reverse natural currents, momentarily converting depositional areas into erosional hotspots. Experimental work shows that drawdown leads to a temporal spike in near-bed velocity—up to 0.7 m/s in shallow estuaries—which is sufficient to entrain silt, clay, and even fine sand [84, 93].

Moreover, the intermittent nature of ship passages means that sediments do not experience continuous shear but instead undergo repeated shocks. This contributes to cumulative degradation of cohesive sediment beds and increased turbidity in affected regions over time [29].

Ship-generated waves exert substantial but short-lived forces on sediment beds, particularly through high-energy drawdown and sustained secondary wave action. These waves drive local resuspension even under minimal ambient currents, leading to sediment mobilization followed by rapid redeposition. Propeller wash and wave-induced orbital velocities further exacerbate the effect, making navigation channels prone to high turbidity and maintenance dredging demands. Accurate modeling of these dynamics requires coupling wave hydrodynamics with sediment transport modules, including representations of time-dependent shear stress, critical entrainment thresholds, and settling velocities.

2.5 Gaps in the Literature and Justification for the Study

Despite significant progress in modeling ship-generated wave impacts on coastal systems, notable gaps remain in the literature concerning inland and estuarine environments, particularly those influenced by confined geometries and low-energy flow regimes. One major deficiency is the limited focus on inland waterways like the St. Lawrence River, where the interaction between low background currents and intense, short-lived ship-generated wave forces presents a unique erosional mechanism not fully captured by existing models.

Most existing research emphasizes short-term or event-based analysis of ship-generated wave dynamics, focusing on individual passage events rather than continuous, cumulative effects. However, long-term sediment resuspension, turbidity, and shoreline retreat are often governed by repetitive stress events, requiring models that account for seasonal patterns, operational schedules, and climatic variability. This lack of temporal resolution limits the predictive capability of conventional modeling approaches, particularly when considering morphological feedback or adaptive shoreline response.

While tools such as DHI MIKE 21 and MIKE 3 are widely used for hydrodynamic and sediment transport modeling, challenges persist in reproducing nearshore sediment dynamics in confined or regulated river sections. In many applications, wave-sediment models are implemented with idealized or simplified bathymetry, omit explicit treatment of drawdown-return-flow coupling, and do not resolve nonlinear secondary waves, all of which are important for evaluating bank erosion and channel morphodynamics. The USACE Vessel Wake Prediction Tool (VWPT) provides a useful empirical framework, yet its generalized parametrization is not designed to capture spatial heterogeneity in geometry, sediment types, and hydrologic regimes.

A further limitation is the underutilization of advanced wave separation methods, which are essential for distinguishing between primary drawdown waves, secondary divergent waves, and wind-induced components. Failure to isolate these signals can lead to misattribution of sediment dynamics, underestimating the role of ship-induced waves. Techniques such

as Fourier transform filtering, empirical mode decomposition (EMD), and machine learning-based classifiers have been successfully applied in broader wave and signal processing research but have not yet been applied in applied ship-generated wave studies.

Another methodological gap is the absence of quantitative regression analysis linking ship characteristics (e.g., draft, speed, hull shape) with ship-generated wave energy, shear stress, or erosion impact. Existing studies generally provide deterministic or parametric formulations (e.g., vessel length–wave height relationships) rather than statistically grounded regressions against observed turbidity spikes or measured shoreline change [49, 56]. As a result, most modeling frameworks remain calibrated on vessel descriptors rather than site-specific data, which limits adaptability and regional relevance.

In recent years, machine learning (ML)—particularly Long Short-Term Memory (LSTM) neural networks—has shown strong performance in hydrological forecasting, sediment transport prediction, and wave time-series modeling [94–96]. Within the shipping and wave literature, ML has been applied to ship motion prediction [97, 98], wave spectrum or sea-state estimation from ship responses [99, 100], and wake identification in estuarine settings [101]. However, no published studies apply ML (including LSTM) to ship-wake-induced sediment dynamic in rivers or confined waterways for example, forecasting turbidity pulses, resuspension events responses driven by vessel wakes. This gap is notable because ship-wake processes are nonlinear and temporally structured; the growing availability of AIS vessel tracks, high-frequency water-level records, and turbidity sensors provides suitable inputs for sequence-learning models that could enable dynamic forecasting of ship-wake-induced sediment fluxes.

The current study addresses these gaps through a region-specific investigation along the St. Lawrence River, focusing on the stretch between Morrisburg and Summerstown. This reach is characterized by confined channel geometry, mixed sediment banks, and relatively low ambient currents—conditions under which ship-generated wave-induced erosion processes are particularly sensitive and poorly understood. Preliminary field observations at this site indicate high-frequency spikes in turbidity correlated with vessel passages, as well as repetitive erosion–deposition patterns near navigation channels. These features make it an ideal testbed for advancing ship-generated wave modeling techniques.

In summary, while the use of numerical models for wave and sediment transport is well-established, current literature lacks: (1) inland-focused, long-term ship-generated wave impact studies; (2) methods integrating wave signal decomposition; (3) data-driven tools such as regression or LSTM for pattern extraction and prediction; and (4) high-resolution validation datasets for confined or regulated rivers like the St. Lawrence. The proposed study directly addresses these gaps by integrating wave–current modeling, wave separation techniques, statistical regression, and exploratory machine learning, offering a comprehensive framework for understanding and forecasting ship-induced shoreline erosion in inland settings.

3 Methods

This chapter outlines the multi-method approach adopted to investigate the dynamics of ship-induced waves and their influence on shoreline erosion and sediment dynamics in the St. Lawrence River, particularly the reach between Morrisburg and Summerstown. The methodology integrates empirical field investigations, hydrodynamic modeling using MIKE 21, statistical regression, and machine learning techniques including Long Short-Term Memory (LSTM) networks. Unlike prior studies that primarily rely on synthetic or laboratory wave conditions, this research utilizes real-time vessel passage data and in-situ wave and turbidity measurements to better reflect local physical processes. Wave signal decomposition was carried out to separate primary and secondary ship-generated wave components using time-domain filtering and spectral techniques, followed by multiple regression analysis to link hydrodynamic forcing with sediment response indicators such as turbidity and bed shear stress. In addition, LSTM networks were implemented to predict time-lagged sediment concentration under varying ship-generated wave regimes, aiming to capture both short-lived drawdown impacts and sustained wave-induced suspensions. This hybrid methodology ensures high temporal resolution, process fidelity, and predictive capability necessary to understand localized erosional hotspots and assess long-term management implications.

3.1 Study Area and Overview

The St. Lawrence River, a major North American waterway, flows through Canada and the United States, connecting the Great Lakes to the Atlantic Ocean. It serves as the primary drainage outflow of the Great Lakes Basin, extending approximately 550 kilometers with a drainage basin exceeding 1.3 million square kilometers. As the largest river in Canada and the fourth largest in North America by discharge, the St. Lawrence exhibits diverse hydrological and geomorphological characteristics along its course.

Originating from Lake Ontario, the river flows northeast into the Gulf of St. Lawrence. It is typically divided into three main segments: the upper section characterized by lakes and rapids; the middle section encompassing the Thousand Islands region; and the lower section, which transitions into a broad estuary entering the Gulf. The river supports significant commercial navigation, hydroelectric power production, and various recreational activities. It also provides critical habitat for fish, birds, and aquatic mammals.

This study focuses on a section of the Upper St. Lawrence River from Morrisburg to Summerstown, both located on the Ontario shore. This regulated river reach, located between the Iroquois Dam and the Moses–Saunders Power Dam, spans approximately 55 kilometers and forms part of the international navigation corridor established by the St. Lawrence Seaway system. Commercial vessel traffic operates year-round, subject to ice conditions, with large freighters and tankers transiting in close proximity to both study sites.

The two study locations, Mariatown and Jacobs Island, represent distinct morphodynamic and geomorphic settings exposed to persistent vessel-induced wave activity. Site locations are shown in Figures 8 and 9 of Chapter 4.

Jacobs Island lies near Summerstown on the northern shoreline, within the traditional territory of the Akwesasne Mohawk First Nation. The island is subject to pronounced shoreline erosion, particularly on its north and west sides, which face the deep and steeply sloped

Seaway channel. Field observations and bathymetric data confirm that water depths transition from shallow (less than 1.5 m) to greater than 15 m over short lateral distances, creating steep gradients along the island’s northern edge. In contrast, the east side of the island forms a shallow, gradually sloping platform extending toward Stanley Island, with maximum measured depths of approximately 1.5 m at 200 m from shore. The island hosts numerous seasonal cottages and permanent residences, and is partially protected with rock revetments and riprap, especially along the north shore.

Mariatown is located near Morrisburg on the north shore and encompasses a shallow embayment known as Mariatown Bay. This embayment was formed through backwater expansion following Seaway regulation, resulting in a broad, gently sloped shoreline with extended shallow zones. Field measurements indicate that depths remain below 1.5 m for over 200 m offshore, followed by a sudden transition to the Seaway channel beyond Canada Island. The site includes a mix of residential and commercial properties, with shoreline areas susceptible to wave-induced erosion due to their unarmored character and open exposure to vessel traffic.

In both locations, the study analyzes the shoreline response to repeated ship-generated wave exposure. By examining two contrasting settings—one steep and armored, the other shallow and unprotected—the research evaluates morphodynamic processes driven by vessel waves within a controlled river system.

3.2 Data Collection and Instrumentation

This research employed a multifaceted data collection strategy to investigate ship-generated wave dynamics and their effects on shoreline erosion in the Upper St. Lawrence River. The approach integrated physical measurements, geospatial data, environmental monitoring, and high-frequency wave and turbidity logging over two seasonal deployment campaigns (June–October 2022 and March–October 2023). Data collection emphasized not only the physical processes affecting sediment resuspension and erosion but also the instrumentation design, maintenance protocols, and field challenges inherent to long-term deployments in dynamic riverine settings.

The data of the ship passage was recovered from the enhanced maritime situational awareness (EMSA) system [14], which aggregates and enriches Automatic Identification System (AIS) feeds, allowing the identification of the frequency, class and trajectory of the vessel for both study sites. This dataset was critical for generating the synthetic ship-wave forcing time series used in subsequent modeling and for validating wave events captured in the logger records. Information was cross-referenced with the external AIS databases, such as MarineTraffic, to construct a one-year passage inventory.

Bathymetric data were obtained from the Canadian Hydrographic Service Non-Navigational (NONNA) dataset. These depth contours, based on recent hydrographic surveys, were used in mesh development for MIKE 21 modeling and to interpret wave focusing and energy dissipation near shorelines. Jacobs Island is situated along the north bank of the Seaway, with steep drop-offs west and north of the island toward the deep navigation channel, while the eastern side is shallower and more gradual. Mariatown Bay is a shallow embayment created by the post-Seaway water level increase, with a depth of less than 1.5 m extending 200 m from shore before a steep slope toward the channel.

Wind speed, direction, and water discharge data were sourced from the U.S. National Weather Service [102], at the Ogdensburg Airport meteorological station (June 2022 and October 2024) and from the Water Survey of Canada gauge at Cornwall, Ontario, covering the same periods. These data informed both the domain-scale hydrodynamic modeling and interpretation of background sediment transport conditions. Additionally, communication with the International Lake Ontario–St. Lawrence River Board [103], enabled access to historic and real-time gate operation records for the Moses–Saunders and Iroquois dams (Cornwall and Iroquois, Ontario) for 2022–2024.

To evaluate long-term shoreline retreat and wave-induced erosion, erosion rod was installed along the Mariatown shoreline in June 2022. The rod served as fixed georeferenced benchmark for GPS surveys and visual shoreline change monitoring. One such rod is shown in Figure 2, where its base marks the initial shoreline toe. The rod also served as a reference for local stakeholders involved in shoreline restoration initiatives.



Fig. 2 Erosion rod installed at Mariatown Bay shoreline (June 2022).

Wave and turbidity data were recorded using six RBR Duo3 D.TU loggers, each equipped with pressure and optical turbidity sensors, and one RBR Wave 16 logger for higher-frequency wave analysis. The instruments are shown in Figure 3.



Fig. 3 RBR Duo3 D.TU (left) with 2 Hz turbidity, pressure, and depth sensors; RBR Wave 16 (right) with 16 Hz pressure and depth sampling capabilities.

The Duo3 sensors sampled at 2 Hz and were deployed for full seasonal cycles, while the Wave 16 operated at 16 Hz for shorter bursts (2 weeks), due to battery life and memory limitations, at each site to resolve high-frequency ship wave trains and wind waves. The instrumentation was housed in custom-built aluminum mounts (Figure 4), composed of a modular frame and detachable feet, enabling stable riverbed deployment and field access for desiccant and battery replacement during data retrieval.

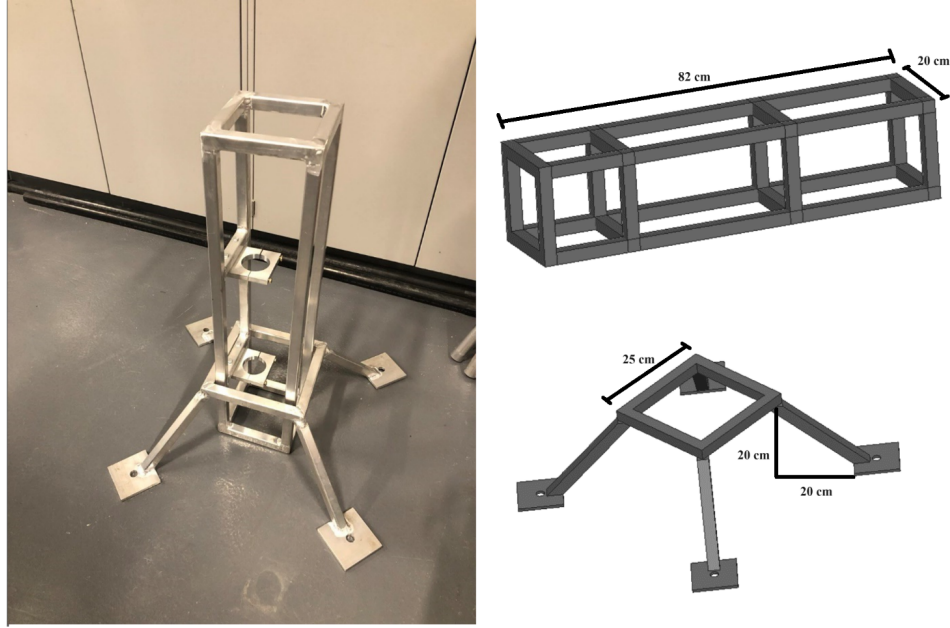


Fig. 4 Custom-built aluminum instrument mount with detachable legs (right: schematic, left: field photograph).

To complement sensor data and support event-based wave attribution, an AXIS P1378-LE network cameras were installed at each site. These cameras were equipped with motion detection and infrared night vision, and programmed to record 7-minute clips (2 minutes before and 5 minutes after) for every passing vessel identified in the frame. The video logs, archived monthly, provided corroborated visual data to link the type and direction of the ship with the wave and turbidity signatures in the logger records. The camera installation frames are shown in Figure 5.



Fig. 5 Installed Axis cameras at Jacobs Island (left) and Mariatown Bay (right) for event-based wave and turbidity attribution.

The resulting dataset included:

- 2 Hz continuous pressure and turbidity data over approximately 180 days across two years;
- 16 Hz high-resolution wave pressure data at each site for 2 weeks;
- Ship passage logs, cross-referenced by video imagery and logger timestamps;
- Erosion rod displacement data from field visits and photogrammetric comparison;
- Environmental background data (wind, discharge, and water level) from federal stations.

A representative logger record from July 14, 2022, is shown in Figure 6, demonstrating the strong correlation between pressure change, turbidity spikes, and depth fluctuations due to vessel-generated drawdown.

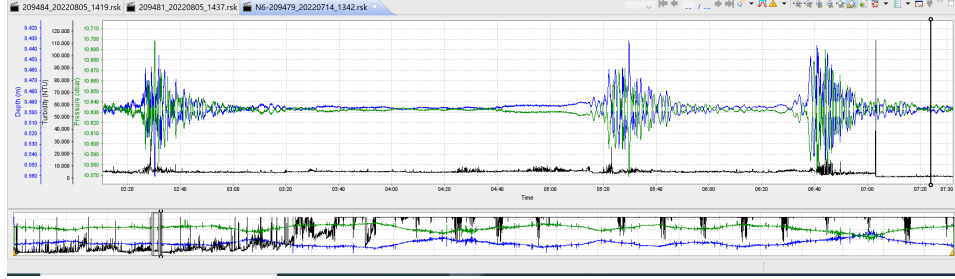


Fig. 6 Wave logger output at 2 Hz (July 14, 2022): blue = depth (m), black = turbidity (NTU), green = pressure (dbar).

The data collection campaign encountered several logistical and environmental challenges. Access to Jacobs Island required coordination with private landowners and relied on small boat transport for instrument maintenance. Winter ice formation halted deployments from November to March, and turbidity sensors occasionally experienced algae fouling (Figure 7) and saturation from auto-gain settings (Figure 8). These issues were addressed by switching sensors to manual gain (fixed at 2500 NTU), implementing a rigorous cleaning schedule, and engaging local stakeholders to assist with interim field checks.



Fig. 7 Algae fouling of turbidity sensor and mounting frame during summer deployment.

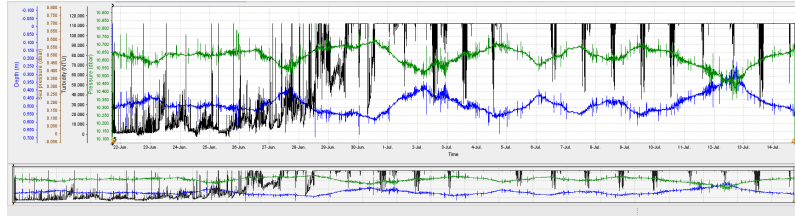


Fig. 8 Sensor over-saturation due to auto gain setting (Jacobs Island, 2022).

Despite these limitations, the dataset acquired forms a robust observational foundation for the wave-sediment modeling and signal separation analyses detailed in subsequent chapters. The rigorous design, redundancy, and integration of physical and visual records ensure that ship passage effects are isolated with high confidence and linked directly to sediment disturbance in both shallow and steep nearshore zones across the study area.

3.3 Data Analysis and Modeling Framework

The analytical procedures applied in this research are described across Chapters 4, 5, and 6, each corresponding to a distinct component of the study. To avoid unnecessary repetition, detailed descriptions of the methods, datasets, processing steps, and validation procedures are provided in the methodology subsections of each respective chapter.

Chapter 4 addresses the processing and analysis of field data related to ship-generated wave events and sediment resuspension. High-frequency wave and turbidity data were obtained from six nearshore logger stations. Ship passages were identified through synchronization with EMSA logs and camera footage. Signal decomposition methods were applied to isolate primary and secondary wave components, and erosion rod measurements were used to support interpretation of nearshore responses.

Chapter 5 presents a statistical modeling framework for estimating turbidity and near-bed shear stress as a function of vessel parameters. The analysis includes multivariate regression and bidirectional Long Short-Term Memory (LSTM) models. Inputs consist of vessel characteristics (e.g., speed, draft, length) and wave-derived hydrodynamic variables. The models incorporate time-lagged predictors to account for delayed sediment response. Full training procedures and performance metrics are described within the chapter.

Chapter 6 outlines the implementation of a process-based numerical modeling approach using the MIKE 21 system. A coarse-resolution hydrodynamic nesting model was constructed for a 55 km reach of the Upper St. Lawrence River. High-resolution wave and sediment transport simulations were performed for two study sites using MIKE 21 SW and MIKE 21/3 FM. Ship-induced wave forcing was generated using the Vessel ship-generated wave Prediction Tool (VWPT), and synthetic time series representing 2,500 ship passages were introduced as model input. Cohesive sediment dynamics were simulated using a Partheniades-type entrainment formulation and validated against turbidity-derived SSC.

Each chapter focuses on a specific aspect of the analysis and applies methods suitable to its scope and objectives. For clarity and to avoid redundancy, methodological details are provided only within the relevant chapters and not repeated here.

4 Ship-generated wave-induced sediment dynamics in upper St. Lawrence River: Analysis of field data

4.1 Abstract

This study examines the effects of combined ship-generated waves and wind-driven waves on sediment dynamics in the upper St. Lawrence River, focusing on two sites at Mariatown and Jacobs Island in Ontario, Canada. Six loggers installed at the two study sites recorded wave and turbidity data over a period of 300 days to distinguish the influences of natural versus ship-induced waves on sediment resuspension. The findings indicate that wind-driven waves regularly resuspend sediment, establishing a baseline turbidity level, while ship-generated waves cause short-lived but intense turbidity spikes, particularly in shallow zones with fine sediment.

Spectral signal analyses, including synthetic natural wave modeling and frequency-based filtering, are used to isolate the frequency characteristics of primary and secondary ship-generated waves from those of natural wind waves, enabling a focused assessment of each wave type's impact on sediment dynamics. Wavelet analysis is applied as a validation tool to confirm the spectral localization of separated wave components. The study demonstrates that factors such as water depth, sediment type, and proximity to the navigation channel strongly influence local turbidity responses.

While historical shoreline imagery is used to provide spatial context, shoreline change was not formally analyzed in this study. Overall, the results offer a replicable framework for isolating wave contributions to sediment resuspension and support future efforts in sustainable sediment and shoreline management in modified river environments.

4.2 Introduction

Shoreline erosion presents an ongoing challenge along the banks of major rivers, carrying substantial environmental and economic repercussions. This issue results from a mix of natural forcing factors, such as wind and water currents, alongside human activities such as increasing ship traffic. For instance, rising ship traffic on the St. Lawrence River has intensified the erosion risk [104–107]. Notably, the St. Lawrence River serves as a critical waterway for transporting over 200 million tons of cargo annually and supports diverse ecosystems, linking the Great Lakes to the Atlantic Ocean [108]. The combined impact of growing maritime activities, natural hydrodynamic forces, and modifications to the riverbed contributes to heightened sediment disturbance and turbidity, ultimately affecting both natural landscapes and shoreline stability [105, 109, 110].

While processes driving sediment dynamics and shoreline degradation have been studied across various riverine settings, debate persists on the relative contributions of wind-generated waves, seiche activity, and anthropogenic forces such as ship-generated waves. Some research underscores the influence of wind-driven waves in broader river sections, where these waves generate enough energy to suspend and transport sediment, leading to gradual shoreline erosion [46, 53]. In high-traffic navigation areas, however, the dominant erosive force is often ship-generated waves, especially in narrow channels where vessels frequently pass, as documented in several studies [51, 58, 105, 111–114].

Recent research underscores the site-dependent influence of various wave types. Didenkulova et al. [115] examined the combined effects of wind waves and vessel-generated waves on coastal sediment dynamics; however, their focus was on statistical changes in beach profiles rather than wave-type separation. Conversely, Gaskin et al. [112] suggested that in narrower channel sections, ship-generated waves have a more substantial effect due to their concentrated energy and frequent occurrence. Studies by Hofmann et al. [82] and Houser [55] showed that, under certain conditions, ship-generated waves may contribute to erosion in ways comparable to wind waves, thus further study is necessary to understand better the relative importance of ship-generated versus wind waves in various contexts.

Several studies have examined the impact of primary and secondary ship-generated waves on shoreline erosion. According to Scarpa et al. [116], primary waves created by a ship’s water displacement can deeply penetrate the water column, carrying significant erosive energy. Additionally, Bluteau et al. (2023) [117] showed that primary waves generated by ships can produce significant shoreline drawdown and runoff, especially under high-speed transit and shallow water conditions. Göransson et al. [29] and Muscalus and Haas [59] present another view, noting that secondary waves, though smaller, still play a substantial role in sediment suspension and erosion even beyond primary shipping lanes. Detailed analysis of both wave types is hence necessary to determine their individual and combined impacts on shoreline processes.

Sediment dynamics also play a vital role in shaping nearshore conditions. Studies by Bauer et al. [53], Osborne et al. [118], and Figlus et al. [77] showed that both wind and ship-generated waves can suspend and redeposit sediments, adding complexity to short-term shoreline behavior. In low-current areas, this sediment suspension and redeposition cycle can influence turbidity and impact shoreline resilience. This study focuses on nearshore turbidity and sediment resuspension dynamics rather than on net sediment transport or bank erosion caused by geotechnical processes. While shoreline erosion is not formally analyzed, understanding wave-specific sediment resuspension contributes to broader efforts to assess shoreline vulnerability in regulated river systems.

When natural and ship-generated waves coincide, their superposition can either enhance or counteract erosive effects, further complicating the issue. This interaction increases sediment suspension and nearshore stress, making it challenging to differentiate wave-type contributions [119, 120]. Given this complexity, advanced signal spectrum analysis and wave separation techniques are essential for isolating wave-specific impacts on sediment resuspension and shoreline forcing. This study addresses this challenge by introducing a multi-stage separation approach that distinguishes ship-induced waves from wind-driven signals under field conditions.

This study aims to assess the relative influence of wind waves and ship-generated waves on sediment resuspension along the shoreline at two sites adjacent to the St. Lawrence Seaway shipping lane in the St. Lawrence River upstream of Montreal. The sites are Jacobs Island near Summerstown and Mariatown near Morrisburg, both in Ontario, Canada. Ship-generated waves, especially secondary waves, are believed to contribute to shoreline sediment disturbance in this regulated river environment. Concurrently, wind waves and Seaway-induced hydrodynamic changes also influence turbidity patterns [105]. This study involves collection and analysis of synchronous wave and suspended sediment field data, including development of a four-stage, noise-subtraction-based wave separation approach to isolate and differentiate between natural and anthropogenic wave forces. Wavelet analysis was also employed as a validation step to confirm the accuracy of the frequency-based separation and to ensure minimal overlap between components. Additionally, historical aerial photos (when available) and satellite images are used to provide spatial context by tracking changes in shoreline position at Mariatown. The objective of this research is to enhance understanding of the effects of ship-induced and natural waves on sediment resuspension patterns in the upper St. Lawrence River, ultimately supporting future shoreline monitoring and management efforts.

4.3 Data Collection and Methodology

The two field sites are at the upstream and downstream ends of the 55 km reach. Since the construction of the St. Lawrence Seaway in 1958 and the Iroquois and Moses-Saunders power dams, the river's natural currents, sediment flows, and geomorphology have been substantially altered. These projects, designed to facilitate navigation for larger vessels and hydroelectric power generation, are governed by U.S.-Canada cooperation, and significantly affect the river's ecological processes by modifying water levels, sediment deposition, flow velocities, and aquatic habitats [121, 122]. Jacobs Island reflects downstream conditions above the Moses-Saunders Dam, while Mariatown upstream of Cornwall lies downstream of Iroquois Dam.

The Seaway's construction involved large-scale dredging, damming, and canalization that fundamentally altered the river's hydrological and morphological characteristics. More than 3,000 people were displaced from eleven communities, and significant tracts of floodplain were inundated. Shorelines were engineered with riprap, embankments, and artificial channels to accommodate deep-draft commercial vessels, leading to reduced shoreline resilience and changes in wave reflection and sediment transport patterns [123].

Both of the Jacobs Island and Mariatown study sites have unprotected shorelines, making them highly susceptible to impacts from both natural and ship-generated waves. These two locations were selected due to their different bathymetric and geomorphological characteristics and the consideration of landowner approval and safety factors for the long-term deployment of instruments.

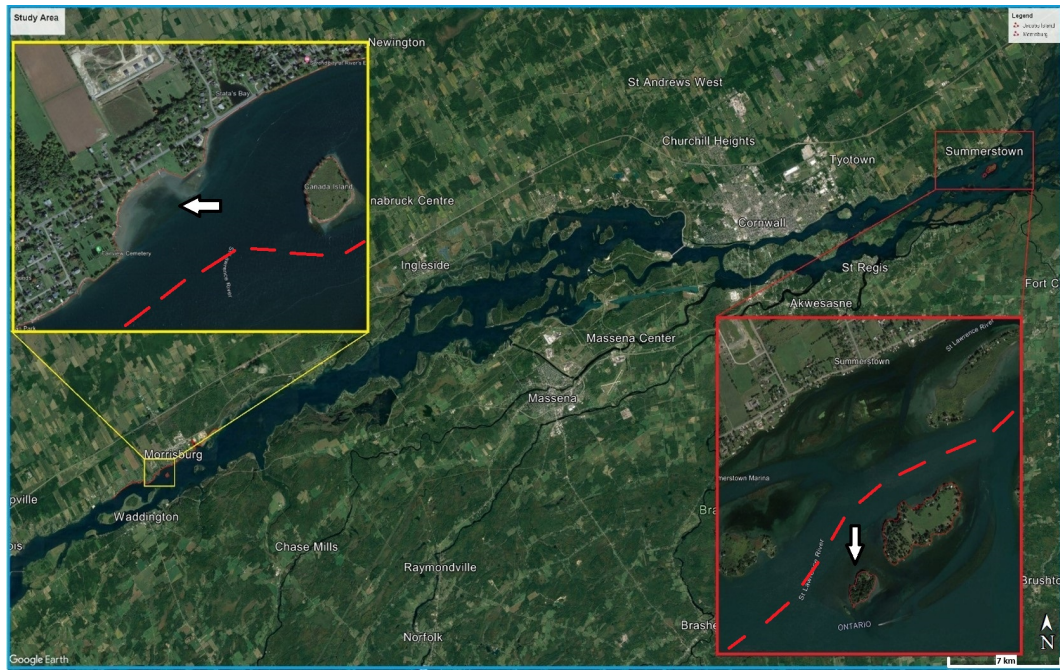


Fig. 9 Study area locations map. Mariatown (yellow) is located to the east at latitude $44^{\circ}53'11.22''\text{N}$, longitude $75^{\circ}11'48.44''\text{W}$, and Jacobs Island (red) to the west at latitude $45^{\circ}2'47.86''\text{N}$, longitude $74^{\circ}33'32.05''\text{W}$. Red dashed lines show the approximate shipping lane. (Source: Google Earth).

Jacobs Island, near Summerstown, Ontario, is located within the Mohawk territory of Akwesasne. Active participation and knowledge sharing with Mohawk community members were integrated into the research process, respecting Indigenous sovereignty and strengthening local understanding of shoreline dynamics. The site is characterized by a shallow area on its eastern side, where the depth reaches approximately 1.5 meters, connecting the island to Stanley Island. This eastern side also features a rocky shoreline structure that functions similarly to a jetty, though not formally engineered. The northern shoreline, adjacent to the

St. Lawrence Seaway, features steep slopes created by the Seaway’s construction, which were subsequently protected with rock riprap. The island’s southern side, facing away from the shipping lane, experiences more natural wave actions, contrasting with the ship-generated wave-dominated northern shore. Jacobs Island was selected based on these unique hydrodynamic conditions, local knowledge contributions, and landowner consent, ensuring the safe and responsible deployment of instruments for long-term data collection.

The Mariatown site, near Morrisburg, Ontario, is located in a shallow embayment within the water level-controlled reach between the upstream Iroquois Dam and the Moses-Saunders Dam downstream at Cornwall. The site is characterized by an unprotected shoreline surrounding the shallow embayment extending around 120 meters from the shoreline to the shipping lane boundary, where the water depth reaches 1.6 meters. Beyond this gradual slope, the riverbed drops off steeply—similar to the slope at Jacobs Island—descending sharply into the deep shipping channel constructed for the Seaway. The contrasting nearshore geometry and channel proximity at Mariatown made it a valuable comparison site for understanding sediment resuspension processes under different exposure and depth conditions.

4.3.1 Historical Shoreline Analysis

A historical shoreline analysis was conducted for Mariatown from 1929 to 2018 using aerial photos [124] and satellite images [125] to determine long-term shoreline changes. Images were georeferenced with ArcGIS Pro, and shorelines from 2018 were manually digitized to provide a reference for time-based assessment. The analysis was divided into two periods: Pre-Seaway Shoreline Stability (1929-1959), using aerial photos from 1929, 1949, and 1953 to assess natural shoreline behavior before the St. Lawrence Seaway’s construction, and Post-Seaway Shoreline Analysis (1959-2018), using aerial photos from 1978 and 1991 and satellite imagery from 2018 to evaluate post-construction changes. Comparative analyses included georeferencing the 1953 and 1991 maps and verifying shoreline positions with Google Earth imagery [125]. A hybrid map in ArcGIS Pro contrasted the 1991 shoreline with 2018 imagery, enabling a comparison of protected and unprotected shoreline segments. The digitized recession distance was used to calculate the annual shoreline retreat rate from 1991 to 2018.

4.3.2 Instrument Deployment and Data Collection

Wave dynamics and sediment suspension were monitored using six RBR Duo3 D.TU wave loggers equipped with turbidity and depth (pressure) sensors, with three loggers deployed at each study site at Jacobs Island and Mariatown (Figure 10). The loggers recorded at 2 Hz throughout two open water seasons (June–October 2022 and March–October 2023), with an approximate five-month gap due to harsh cold weather in winter. The loggers captured wave characteristics and turbidity expressed in Nephelometric Turbidity Units (NTU). At Jacobs Island, the loggers were positioned along both the northern (Seaway-facing, ship-generated wave prone) and southern (naturally wave-exposed) shores. At Mariatown they were deployed across a transect extending from shallow shoreline waters to deeper areas near the shipping lane. The logger placement strategy was designed to capture spatial gradients in wave energy and turbidity from shoreline to channel margin at both sites. A summary of

specific locations, depth, bed type, and turbidity characteristics of each logger at Mariatown and Jacobs Island is presented in Table 6.



Fig. 10 (a) Jacobs Island satellite view and instrument locations (Google Earth), (b) Mariatown satellite view and instrument locations (Google Earth).

Table 6 Loggers specific location, depth, and bed type

Logger	Location	Latitude	Longitude	Depth	Bed Type	Position
N1	Mariatown	44°53'7.64"N	75°11'53.26"W	(20 cm)	Fine sediment	Near shoreline
N2	Mariatown	44°53'6.56"N	75°11'51.19"W	(1.5 m)	Fine sediment	100 meters offshore
N3	Mariatown	44°53'11.15"N	75°11'52.08"W	(50 cm)	Fine sediment	Near shoreline - middle of the bay
N4	Jacobs Island	45°2'49.45"N	74°33'28.25"W	(45 cm)	Rocky bed	Directly faces shipping lane – northeast side of Jacobs Island
N5	Jacobs Island	45°2'49.11"N	74°33'27.89"W	(1 m)	Fine sediment	On the opposite side of the jetty from N4 – east side of Jacobs Island
N6	Jacobs Island	45°2'45.53"N	74°33'27.12"W	(60 cm)	Rocky bed	Positioned not facing the shipping lane – south side of Jacobs Island

Loggers were retrieved monthly for battery exchange, sensor cleaning and redeployment to maintain continuous data collection and address battery life limitations. Additionally, AXIS P1378-LE network cameras with AI motion detection and night vision recorded seven minutes of footage for each ship passage (two minutes before and five minutes after) to confirm wave events visually. Vessel traffic data from Transport Canada's enhanced maritime situational awareness system (EMSA) [105] logs detailing passage times, ship type, size,

and speed were used to relate wave and turbidity measurements to specific ship passages accurately.

Wind data was obtained from Ogdensburg International Airport, the nearest station providing uninterrupted wind records at an hourly scale from January 1, 2022, to January 1, 2024, online through the National Weather Service [102]. Water level data was obtained at 3-minute intervals at Morrisburg (Station 14660) and Summerstown (Station 14940) from Fisheries and Oceans Canada [126].

Data from RBR Duo3 D.TU wave loggers were downloaded and displayed with RBR’s Ruskin software. These visualizations, represented as graphs, validated sensor operation, identified wave and turbidity patterns, and facilitated the establishment of baseline values. Figure 11 showcases data collected at a 2 Hz rate in July 2022, showing the relationship between depth (blue), turbidity (black), and pressure (green). The correlation between turbidity and depth variation was used as a first-level screening method for identifying ship-generated wave-induced sediment disturbance prior to signal separation.

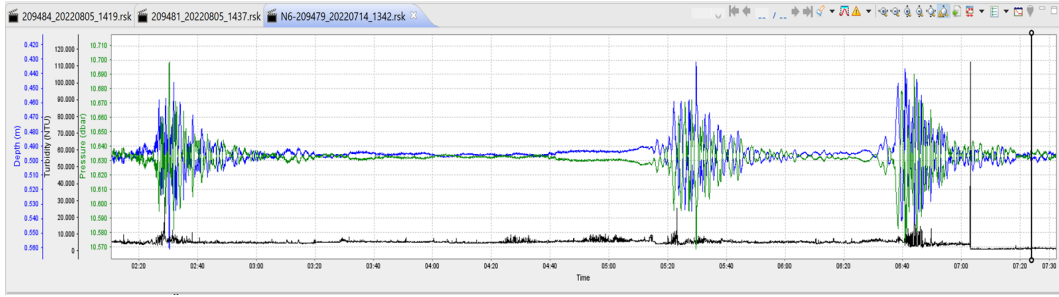


Fig. 11 Data collected on July 14th, 2022, at a 2 Hz sampling rate at Mariatown. The graph displays depth (in meters) in blue, turbidity (in NTU) in black, and pressure (in dbar) in green.

4.3.3 Data Preprocessing and Event Detection

Preprocessing was essential for creating the event detection dataset and distinguishing between natural and ship-generated waves, considering changing circumstances throughout each event. Initial observations of collected data revealed that each ship passage event produces a package of ship-generated waves that is observable for approximately 40 minutes, and the turbidity spikes after high water level fluctuations associated with the wave package.

This synchronization was confirmed using three overlapping sources: wave logger data, camera footage, and EMSA logs. The 60-minute window, including 15 minutes pre- and 45 minutes post-passage, was based on observed turbidity settling periods following ship-induced disturbances, consistent with field calibration results. Figure 12 illustrates a representative ship-generated wave event and the corresponding turbidity response.

A comparison of ship passage timestamps from EMSA logs, camera recordings, and loggers’ data revealed a consistent four-minute delay between the actual ship passage time and the wave arrival recorded by wave loggers at the Mariatown shoreline. An approximate seven-minute discrepancy was noted in the EMSA records relative to the actual passing time.

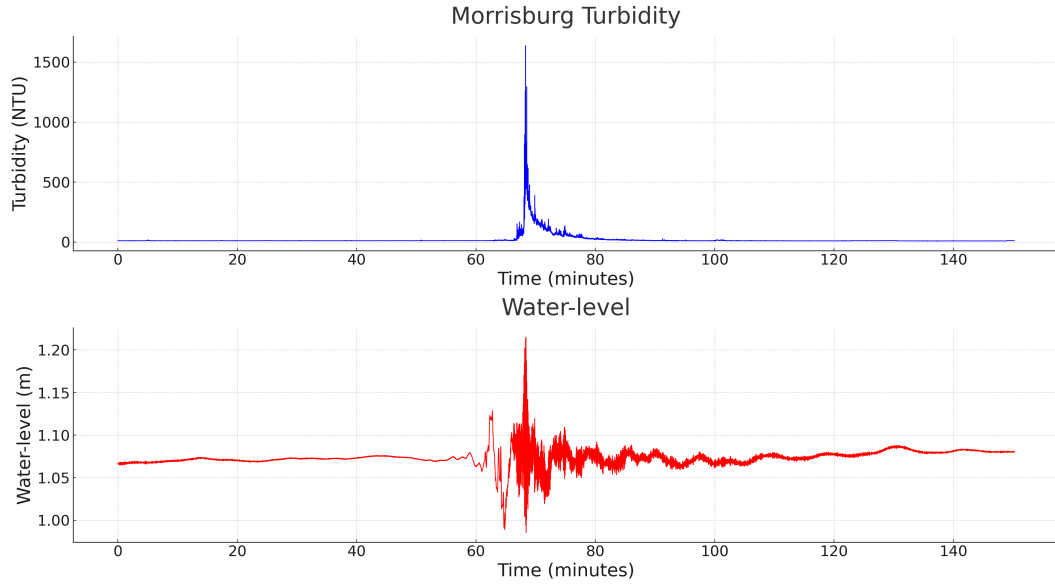


Fig. 12 The water level (red) and turbidity (blue) recordings for one ship passage event at the Mariatown location near Morrisburg on September 21st, 2022.

The timestamps from EMSA records were modified by seven minutes to align with actual passing durations, while the wave logger data was edited by four minutes to correspond with the ship-generated wave’s arrival at the shore. This synchronization made the wave logger data correspond with the actual timestamp of the ship’s passage.

After acquiring the timing alignment and baseline values, a threshold-based method was used to cross-reference the adjusted ship passage durations with wave height and turbidity data to detect ship-generated wave events. A 60-minute timeframe was established for each passage, including 15 minutes before and 45 minutes after the ship passage. Thresholds for depth variations and turbidity fluctuations were established based on a standard ship navigation pattern to detect the depth and turbidity spikes as an indicator for ship passage. The mean water level for each incident was calculated and then deducted from the recorded depth measurement. This resulted in a distinct dataset for each ship passage event’s wave train and turbidity data.

4.3.4 Spectral and Frequency Analysis

The complexity of wave interactions in riverine environments arises from mixing different wave types from ship-generated waves and natural waves. Ship-generated waves consist of two primary components:

1. **Primary Waves (hull-generated waves):** These waves propagate nearly perpendicular to the direction of the ship’s movement, forming diverging wavefronts with low frequencies and high amplitudes. They result from the displacement of water by the ship’s hull and

- can travel long distances, impacting the shoreline significantly [127]. In narrow water bodies, the primary wave can induce a drawdown and subsequent surge at the shoreline.
2. Secondary Waves (Kelvin ship-generated wave): These are generated at the bow and stern of the ship, traveling at an angle relative to the ship's movement and forming a V-shaped ship-generated wave pattern behind the ship. Compared to primary waves, they have a higher frequency and shorter wavelength [128].

As the ship moves, the impact of both primary and secondary waves changes, with their effect on stationary loggers diminishing as the ship travels further away, creating a dynamic pattern in the ship-generated wave structure. Natural waves, such as wind and seiche waves, also contribute to the complexity of riverine environments. These waves exhibit irregular frequencies and amplitudes, adding to the persistent high-frequency dynamics within the river [105].

Despite limitations due to frequency overlap between wind waves and Kelvin ship-generated wave waves, an initial attempt was made to use Butterworth bandpass filters to analyze and isolate wave components and validate the complex nature of ship-generated wave and natural wave interactions. The Butterworth filter was chosen for mixed wave analysis because of its smooth frequency response and low signal distortion [129]. High-pass filters were used to identify wind waves, while low-pass filters were used to detect ship-generated waves [130]. However, as expected, bandpass filtering proved inappropriate for separating ship-generated waves from wind waves due to the frequency overlap of the two signals. This challenge led to the development of a multi-step separation method described below.

This study introduces a four-stage wave separation approach, distinct from wavelet-reliant methods such as Pethiyagoda et al. (2017). The approach consists of: (1) extraction of natural wave conditions using pre-passage data; (2) spectral and frequency-based modeling to generate synthetic wind and seiche wave trains using Gaussian noise extrapolation; (3) signal subtraction to isolate ship-generated wave components; and (4) frequency filtering to separate primary and secondary ship-induced waves.

Power Spectral Density (PSD) analysis was utilized on data from scenarios with and without ship passes at similar wind conditions to identify the wave energy distribution across frequencies. This included computing the power spectrum for recorded depth (wave) fluctuations in both scenarios. The PSD was calculated using the Welch method [131], as implemented in Python's SciPy library, and is given by the equation:

$$P_{xx}(f) = \frac{1}{L} \sum_{k=1}^L \frac{1}{N_{\omega}} \left| \sum_{n=0}^{N_{\omega}-1} x_k(n) \omega(n) e^{-j2\pi f n / N_{\omega}} \right|^2 \quad (21)$$

where:

- $P_{xx}(f)$ is the Power Spectral Density at frequency f ,
- L is the number of segments,
- N_{ω} is the number of points in each segment,
- $x_k(n)$ represents the signal in segment k at sample n ,
- $\omega(n)$ is the windowing function applied to the segment.

Stemming from this analysis, a simplified approach was developed to separate the natural waves from each event wave train using the pre-ship passage conditions. The natural

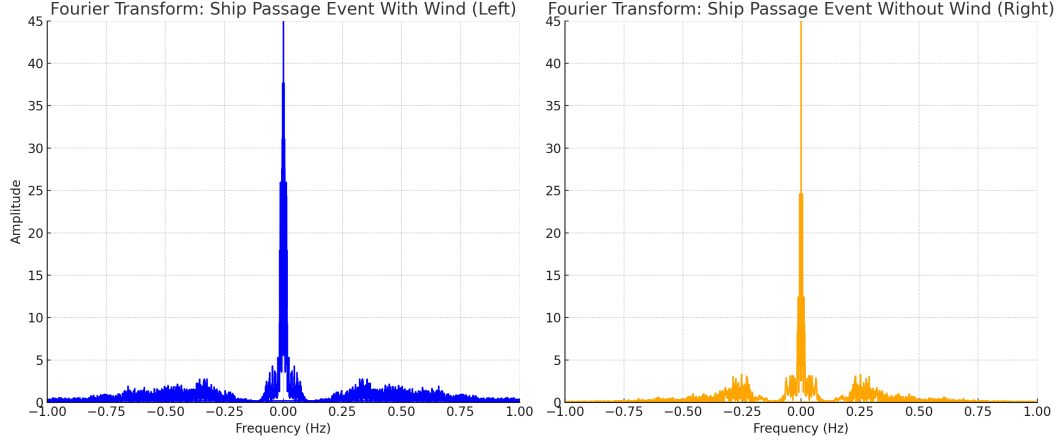


Fig. 13 (left) Fourier transform for a sample wave event due to a ship passage event with no wind present, and (right) Fourier transform for a sample wave event due to a ship passage event with wind present. FFT is shown as a standard two-sided spectrum; negative frequencies represent mirrored components of the real-valued signal.

waves were isolated 15 minutes before each ship passage to provide a baseline, considering that ship-generated wave impacts can persist for approximately 40 minutes. For this 15-minute period of natural wave data, a low-pass Butterworth filter was applied to separate the long-period seiche waves and short-period wind waves. These two natural wave trains were then extrapolated in time to create synthetic natural wave data for the remaining 45-minute ship passage event duration. Specifically, the natural wave signal was reconstructed synthetically using periodic continuation of the mean frequency of the seiche waves for the seiche oscillations and Gaussian noise generation matched to the observed wind wave spectrum for the wind waves. The simulated natural wave pattern was compared to equivalent conditions without ship passages. Additionally, the natural wave simulation was conducted during the first 15 minutes of the dataset before the ship passage, and the results were compared with the actual recordings from loggers during the corresponding period.

Following verification, the synthesized natural wave data was deducted from the event wave train to isolate the ship-generated wave component. For the remaining ship-generated wave signal, spectral analyses were performed to isolate the low-frequency primary waves from the higher-frequency secondary Kelvin ship-generated wave waves, utilizing a Butterworth bandpass filter established through PSD analysis with cutoff frequencies of 0.005 Hz, 0.03 Hz, and 0.15 Hz.

The introduced wave separation approach was validated by comparison to a conventional wavelet transform method applied to ship-generated waves, wind waves, and turbidity data using Python's PyWavelets library. This time-frequency analysis aimed to identify transient features indicative of ship-generated waves and further refine the separation of wave components by analyzing the temporal and frequency components of wave interactions, serving solely as a validation tool and not for wave separation.

$$W(a, b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t) \psi^* \left(\frac{t-b}{a} \right) dt \quad (22)$$

where:

- $W(a, b)$ is the wavelet coefficient at scale a (related to frequency) and position b (related to time),
- $x(t)$ is the wave signal,
- a is the scale parameter that dilates or compresses the wavelet,
- b is the translation parameter that shifts the wavelet in time,
- ψ is the mother wavelet,
- ψ^* denotes the complex conjugate of the wavelet function, and
- the term $\frac{1}{\sqrt{|a|}}$ ensures energy normalization and consistency of the transform across different scales [132].

The normalized energy distribution was derived by applying the Continuous Wavelet Transform (CWT), which breaks down each wave component into its time-frequency representation. The energy for each scale, corresponding to a specific frequency, was determined by calculating the squared magnitude of the wavelet coefficients and summing these values over time. To achieve normalization, the energy values for each component were divided by that component's total energy, ensuring the energy distribution totals to one. This output was used to cross-check the accuracy of the frequency-based filtering in capturing distinct ship-generated wave signatures.

The following flowchart (Figure 6) summarizes the spectral wave separation and synthetic signal subtraction methodology used in this study to isolate ship-generated wave impacts from natural wave signals.

4.3.5 Turbidity and SSC Calibration

After separating the primary and secondary ship-generated wave components, the next step was to evaluate the impact of both ship-generated waves and natural waves on sediment dynamics along the shoreline. The average turbidity data collected before ship passages served as a baseline for natural wave-induced turbidity. This baseline value was then subtracted from measured post-passage turbidity values to calculate ship-generated wave-induced turbidity. It was noted that turbidity increases primarily indicate local sediment resuspension. This may not directly translate to long-term shoreline erosion unless accompanied by sustained sediment transport away from the site or geotechnical slope failure.

The turbidity sensors were calibrated during the winter deployment gap before data collection in the spring of 2023, responding to potential errors in first-year data collection. All six loggers were tested with two samples, before and after the calibration, to identify any calibration discrepancies in the turbidity sensor readings and to determine the turbidity-SSC relationship. Figure 15 presents the loggers' turbidity sensor test results.

The following linear equation states the link between turbidity and SSC:

$$\text{SSC (g/L)} = a \times \text{NTU} + b \quad (23)$$

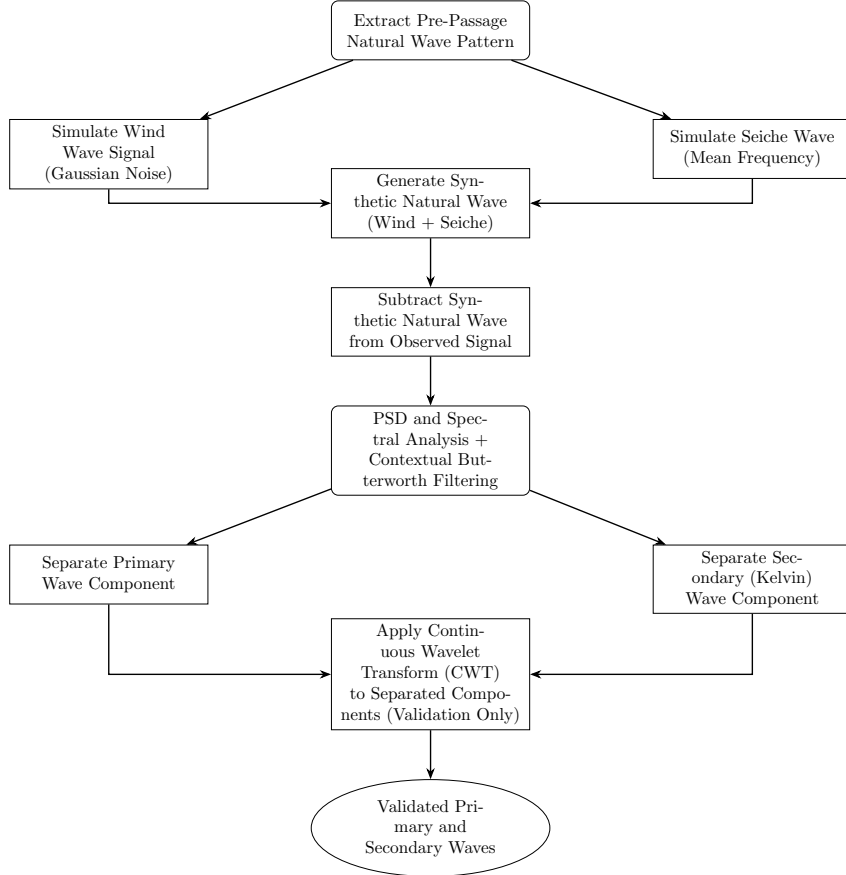


Fig. 14 Step-by-step flowchart for wave separation and validation procedure.

This equation enables the correct conversion of turbidity data to SSC, thus permitting a more accurate evaluation of sediment transport and suspension dynamics, where a and b are site-specific constants determined from the calibration experiments [133]. For the study sites, the calibrated equation is given by:

$$\text{SSC (g/L)} = 0.0019467 \times \text{NTU} - 0.0394 \quad (24)$$

A clear link was developed using the lab test results between turbidity (NTU) and suspended sediment concentration (SSC in g/L) obtained from samples collected at the field site. This relationship enabled sediment concentration to be determined from collected turbidity data and quantified the contribution of natural waves and ship-generated waves to sediment resuspension in the study areas. A cumulative assessment was accomplished using the average turbidity value for each of natural and ship-generated waves, the respective duration of the wave train for each event, and their frequency throughout the year using data from Seaway ship passages and wind conditions.

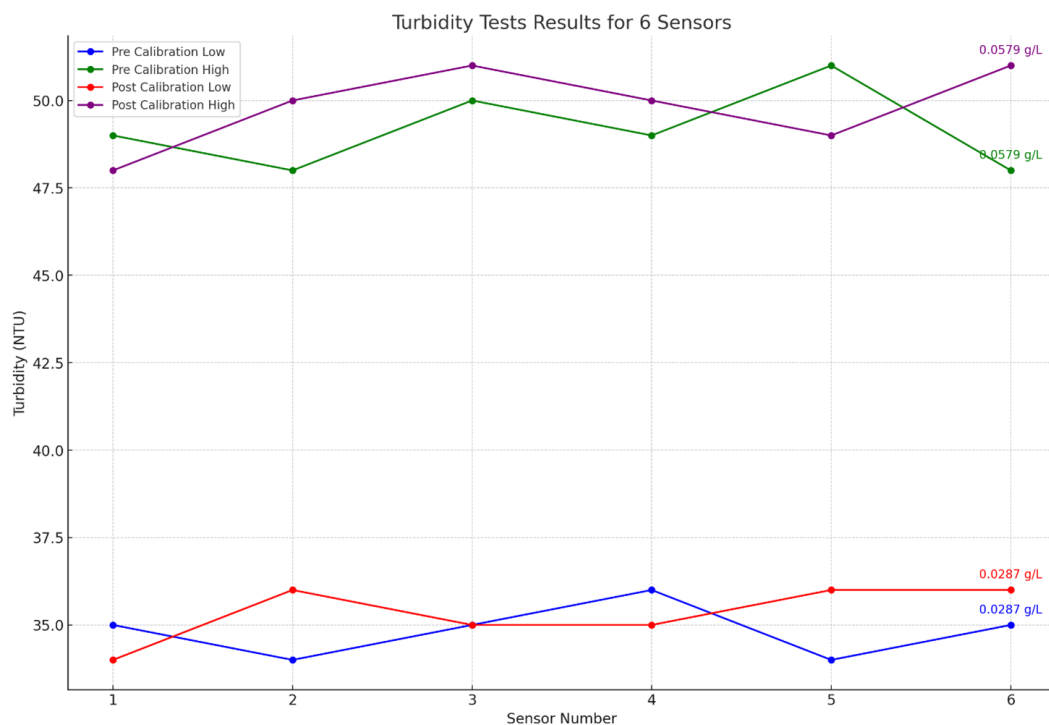
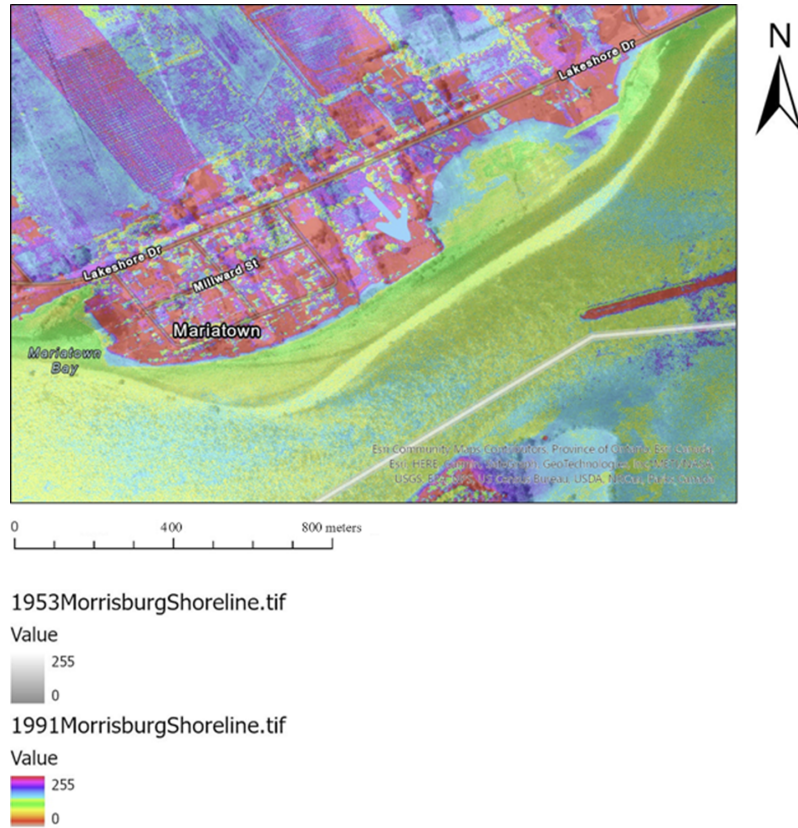


Fig. 15 Loggers N1 to N6 Turbidity sensor calibration test results before and after the calibration of the instrument.

4.4 Results and Discussion

4.4.1 Historical Shoreline Change Analysis

Historical analysis highlights the influence of St. Lawrence Seaway construction on shoreline erosion patterns in the Morrisburg–Summerstown reach of the river. Between 1929 and 1953, the pre-Seaway shoreline remained stable, protected by natural vegetation and engineered channel walls. However, following the Seaway’s construction in the late 1950s, substantial shoreline recession occurred along unprotected sections, including the formation of a distinct embayment near Mariatown. Subsequent georeferenced comparisons between 1991 and 2018 indicate an average erosion rate of approximately 0.3 meters per year. These observations underscore the long-term geomorphological impact of the Seaway on shoreline configuration. To support spatial comparisons across time periods, aerial photographs from 1953 and 1991 were georeferenced using ArcGIS Pro, as illustrated in Figures 16 and 17.



Mariatown Shoreline comparison 1953 vs 1991 (NRC Aerial photos)

Fig. 16 NRC aerial photos from 1953 and 1991 at Mariatown have been georeferenced to form a two-layer comparative map.



Mariatown and Canada Island 1991 vs 2018 shoreline

Fig. 17 NRCan 1991 aerial photo georeferenced against 2018 digitized shoreline (Google Earth) using ArcGIS Pro, showing continued shoreline recession at Mariatown.

4.4.2 Wind Patterns and Logger Exposure

Figure 18 presents a wind rose plot of the daily average wind speed and direction during the data collection period. Winds mainly originate from the southwest direction. This dominant wind direction directly impacts the loggers N1, N2, and N3 at Mariatown and N6 at Jacobs Island.

4.4.3 Initial Data Review and Event Detection Thresholds

An initial investigation of data collected by loggers at Mariatown revealed consistent patterns. Water levels tended to rise during high wind events, and under such conditions, turbidity levels could exceed those triggered by ship-generated waves. Observations across multiple events highlighted the distinct turbidity responses driven by wind versus ship activity, especially at loggers N1, N2, and N3.

Following this initial review of Mariatown site data, the datasets collected from loggers N4 to N6 located at Jacobs Island were also analyzed. The distinct impacts of the loggers' specific locations on their wave and turbidity recordings were examined.

Logger N4, which faced the shipping lane and was situated on a rocky bed, recorded more ship passage events than N5 and N6 due to its direct exposure to ship traffic moving both eastward and westward.

Wind Rose Diagram (June–October 2022 and March–October 2023)

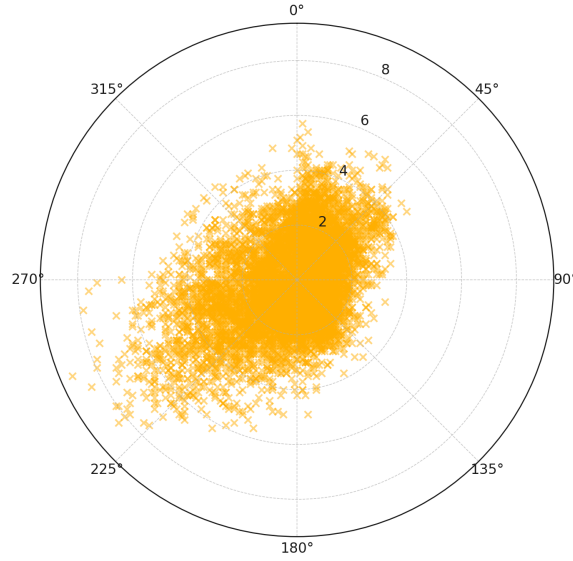


Fig. 18 Wind Rose Diagram showing daily average wind direction and speed (m/s) for June–October 2022 and March–October 2023.

Logger N5 was located on the opposite side of a jetty from N4 and was positioned on a fine sediment bed. It primarily captured east-to-west ship traffic because the jetty partially shielded it from west-to-east waves. Additionally, the recessed embayment between the jetty and the island’s southern edge offered further protection from wave action. Despite relatively stable wave heights, N5 displayed increased turbidity during wind events, attributed to the resuspension of fine sediment from its bed caused by indirect wave energy and reflections from the jetty. A significant rise in turbidity was observed throughout these wind events, even with consistent wave heights.

Logger N6, located on the opposite side of Jacobs Island and thus shielded from the shipping lane, primarily recorded east-to-west ship traffic. This positioning resulted in noticeably lower impacts from ship-generated waves, with wave activity largely reflecting wind wave effects.

This initial data analysis helped clarify the magnitude of hydrodynamic and sediment responses at each logger location, and highlighted the complex interactions between natural waves and ship-generated waves. These insights guided the selection of threshold values for detecting ship passage events during data preprocessing, as summarized in Table 7.

The thresholds for event detection were determined based on the presence of sudden fluctuations in water depth and concurrent spikes in turbidity. Each ship passage event was typically recorded in the dataset as a short drawdown in water level followed by wave fluctuations and a noticeable increase in turbidity. Threshold values were selected through visual inspection of logger-specific time series, by testing multiple combinations of depth and turbidity thresholds, and by cross-checking results across different events and logger sites. This iterative process ensured that the selected double-threshold values effectively distinguished ship passages from naturally occurring wind-wave activity.

Table 7 Threshold turbidity and depth fluctuation values used to detect ship passages for each logger.

Logger	Turbidity Threshold (NTU)	Depth Fluctuation Threshold (m)
N1	130	0.23
N2	120	0.10
N3	30	0.20
N4	30	0.35
N5	120	0.30
N6	50	0.10

4.4.4 Detection Performance and Logger Comparison

Table 8 presents the total number of events detected by ship passages from each logger’s dataset. The total number of passages reported by the Seaway in traffic reports for 2022 and 2023 is 2559 during the data collection period [2, 3].

Table 8 Comparison of detected ship passages by each logger with the Seaway-reported number of ship passages.

Logger	Detected Ship Passages	Seaway-Reported Ship Passages	Discrepancy (Detected - Reported)	Event Detection Accuracy (%)
N1	2483	2559	76	97%
N2	2428	2559	131	94%
N3	2477	2559	112	96%
N4	2492	2559	67	97%
N5	1354	2559	1205	52%
N6	1341	2559	1218	52%

The comparison of total detected ship passage events with Seaway-reported traffic demonstrates the effectiveness of the detection thresholds for ship passage events. N1, N2, N3, and N4 had detection accuracy ranging from 94% to 97%, indicating reliable detection in areas directly facing the shipping lane. Also, lower detection accuracy (52%) for N5 and N6, which were not impacted by west-to-east ship passages, as observed in the initial investigation, aligns with expectations for these loggers.

4.4.5 Spectral Analysis of Ship Waves and Wind Waves

To further investigate the frequency characteristics of ship-generated waves, wind waves, and turbidity, Power Spectral Density (PSD) analysis was conducted. This analysis includes two scenarios: a ship passage event with wind present and a wind-only event with no ship passage but similar wind characteristics to the other scenario. Figure 19 showcases the Power Spectral Density (PSD) results for a detected ship passage with wind present (left) and for a prior period of wind-only conditions (right). Examination of the PSD of these two events reveals the characteristic frequency ranges for ship-generated waves and wind waves, offering insight into how each influences depth changes.

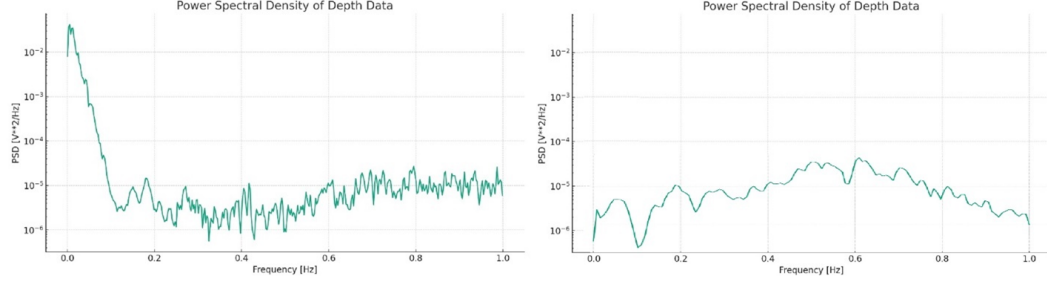


Fig. 19 left) power spectral analysis of a ship passage with wind present on recorded depth changes (wave) data, and right) power spectral analysis of wind event with no ship passage on recorded depth changes (wave) data. Both collected on September 10, 2023 at logger N4.

In Figure 19, the PSD for the ship passage event reveals a strong low-frequency peak around 0.05 Hz, corresponding to the primary waves generated by the ship. Additionally, a moderate energy range from 0.1 Hz to 0.3 Hz likely represents the ship's secondary waves, overlapping with frequencies characteristic of wind-driven waves. In the wind-only period, the energy is more broadly distributed across higher frequencies, with peaks around 0.2 Hz, 0.4 Hz, and 0.6 Hz. This frequency overlap, particularly between 0.1 and 0.3 Hz, highlights the challenge of isolating ship-generated wave effects from wind-driven waves, as both contribute energy within this shared range. However, the unique low-frequency peak at 0.05 Hz in the ship passage provides a distinct marker of ship-induced activity, while the wind-only event's higher frequency range of up to 0.8 Hz is typical of wind-driven waves. These distinctions highlight the challenges in isolating each wave type in overlapping frequency bands and the need for a dedicated wave separation approach to isolate ship-generated components from wind wave signals, particularly within the overlapping frequency range of 0.1–0.3 Hz.

4.4.6 Wave Separation

Following the PSD analysis, a targeted methodology was developed to address the overlap between ship-generated wave and wind wave frequencies, particularly within the range of the ship's secondary waves. This approach involved establishing a baseline of natural wave patterns, isolating primary and secondary ship-generated wave components, and reducing high-frequency wind wave interference to improve separation accuracy. Natural waves were isolated using data from the 15 minutes preceding each ship passage to create a reliable baseline when no ship-generated wave effects were present. Low-pass Butterworth filters were applied to separate long-period seiche waves from the captured natural wave train, while a bandpass filter targeted short-period wind waves. The average frequency of seiche waves was used to synthesize these waves, and Gaussian noise was applied to simulate the wind wave pattern over the whole event duration. The synthesized wind wave data was then compared to conditions before ship passage and subtracted from the event's combined wave train, effectively isolating the ship-generated wave. This method was validated by comparing simulated wind wave data with actual data from the pre-ship passage period, confirming

the accuracy of the approach in isolating natural wave patterns. Despite the practical application of this method, approximately 8% of the wind wave energy remained in the residual signals due to high-frequency components that were challenging to filter completely. This unresolved portion introduced some noise into the separation of secondary waves, particularly in the high-frequency range where wind and ship wave energy overlap. While this may result in minor residual contamination of the ship-generated wave signal—especially for secondary waves—the overall separation quality was found to be sufficient for interpreting wave dynamics and estimating associated turbidity responses. The separation method was further validated using wavelet scalograms, confirming that the primary and secondary ship wave components remained clearly identifiable in both time and frequency domains.

The PSD analysis allowed further separation of the ship-generated wave into its primary and secondary components. The primary waves, concentrated around 0.05 Hz, represent the low-frequency, long-period waves generated by the ship’s initial passage. The secondary waves, observed between 0.1 Hz and 0.3 Hz, are shorter-period waves that often overlap with the frequencies of wind-driven waves. Additionally, the superposition of overlapping frequencies led to a resonance effect, amplifying specific frequency ranges and further complicating the isolation of individual wave components. These challenges underscore the inherent difficulties in separating overlapping frequency contributions in complex, mixed-wave environments.

Figure 20 provides an example of the wave separation methodology results, demonstrating the effectiveness of this approach for isolating different wave components. This figure includes sub-plots for turbidity, wind waves, seiche waves, and ship-generated wave components (primary and secondary waves), illustrating the method’s ability to distinguish natural and ship-induced waves.

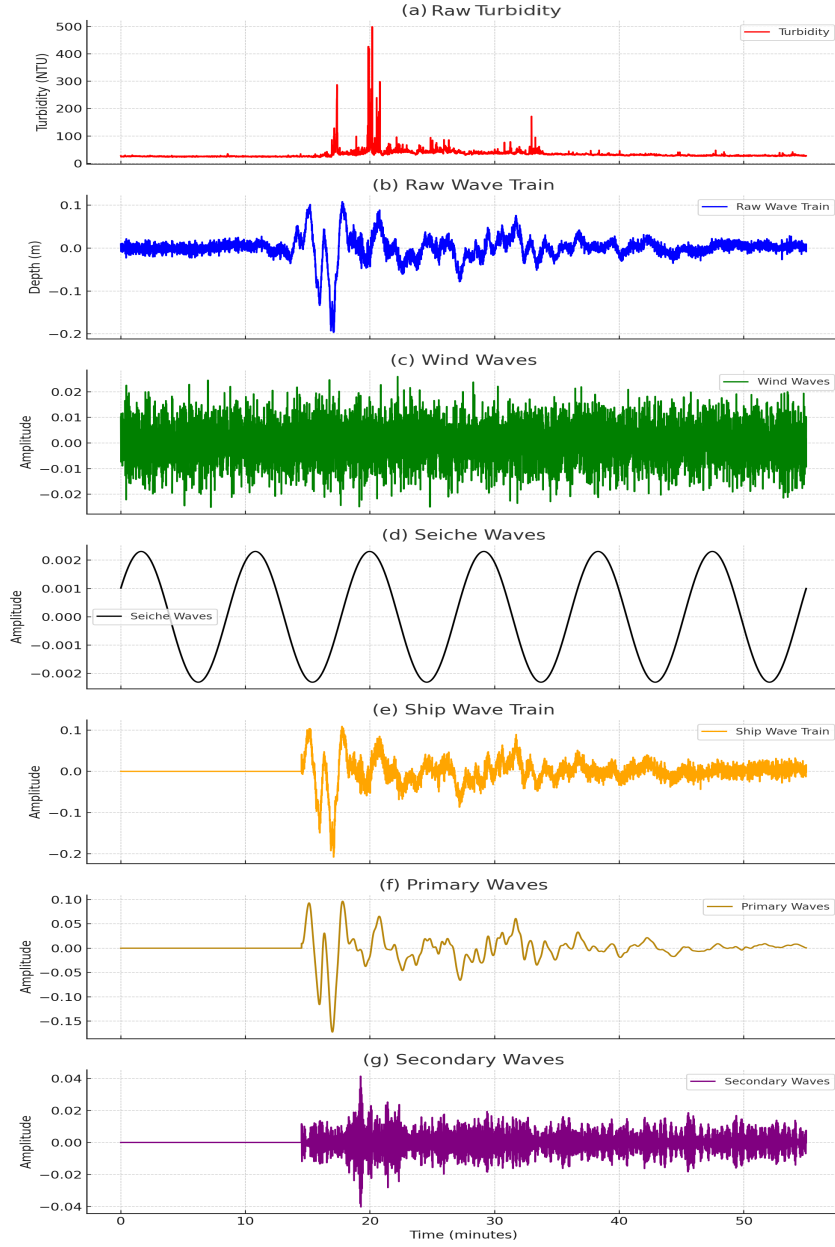


Fig. 20 Time-series analysis of the ship-generated wave event recorded by logger N1 on 2023-09-10. (a) Turbidity levels showing distinct peaks aligned with ship passage times. (b) Main wave train calculated as the depth minus the dynamic mean water level. (c) Minimal wind-wave activity. (d) Seiche waves. (e) ship-generated wave train. (f) Primary ship-generated waves. (g) Secondary ship-generated waves.

The offset between the peak wave activity and the turbidity response observed in Figure 12 is attributed to the time required for sediment to be entrained and transported vertically to the turbidity sensor, especially at the shallow nearshore logger N1. While primary ship waves clearly dominate in amplitude—approximately an order of magnitude greater than secondary waves in this event—the secondary wave field is more persistent and may sustain mixing after the primary peak. Additionally, the interaction between primary and secondary wave trains is irregular and nonlinear; in some cases, their superposition may enhance bed stress through constructive interference, while in others it may have a dampening effect depending on phasing and local conditions.

While primary ship-generated waves often initiate turbidity peaks due to their long period and high amplitude, secondary waves, despite lower amplitudes, can contribute to sustained sediment agitation due to their persistence. The relative influence of each wave type on the turbidity response varies between logger sites, depending on observed exposure and the behavior of the sediment. For example, sharp turbidity spikes at N1 coincide with primary wave forcing, while more gradual or prolonged turbidity increases at other locations may suggest a greater role for secondary or wind wave activity.

To further validate the separation results, wavelet scalograms were used to examine the time–frequency properties of individual wave components. Figure 21 presents the scalograms for the same event shown in Figure 20, recorded at logger N1 on September 10, 2023. This specific event was selected for repeated presentation throughout the results to enable comparison of filtering, spectral analysis, and turbidity response. The raw signal scalogram (a) shows the cumulative influence of all wave types. Subplots (b) and (c) confirm the frequency localization of primary and secondary ship waves, respectively, while subplot (d) highlights the presence of minimal high-frequency wind wave energy, and (e) displays low-frequency oscillations attributed to seiche waves.

The wavelet analysis was conducted using a Morlet wavelet over a 60-minute window. In this configuration, scale 100 corresponds to a pseudo-frequency of approximately 0.0382 Hz, aligning with primary ship waves. Scale 40 corresponds to 0.0955 Hz, and scale 20 corresponds to 0.1910 Hz, which fall within the ranges associated with secondary ship waves and wind waves, respectively. These results support the spectral separation obtained through filtering and confirm that each component maintains a distinct time–frequency signature.

While wavelet-based methods such as those used in Didenkulova et al. (2011) and Pethiyagoda et al. (2016) have demonstrated effectiveness in decomposing idealized or simulated ship-generated wave signals, these approaches rely on high-resolution, noise-free datasets where wave components are well separated in both time and frequency. In contrast, the field data used in this study contains overlapping wave contributions, irregular bathymetry effects, wind interference, and sensor noise. As such, conventional wavelet transforms, including Morlet-based scalograms, failed to consistently isolate primary and secondary ship waves in the presence of concurrent natural wave energy. Specifically, the scalograms often showed energy spread across broad time–frequency bands, complicating the attribution of peaks to specific wave components. To address these limitations, our methodology employs a synthetic filtering approach combining bandpass filters, Gaussian noise modeling, and spectral subtraction based on pre-event baselines. This enabled more precise reconstruction and separation of wave components in complex, real-world datasets. Unlike previous studies that analyzed single synthetic signals or simplified field conditions, our

approach is designed for multi-event processing and accommodates variable site exposure, bathymetric effects, and noise levels observed in large-scale monitoring deployments.

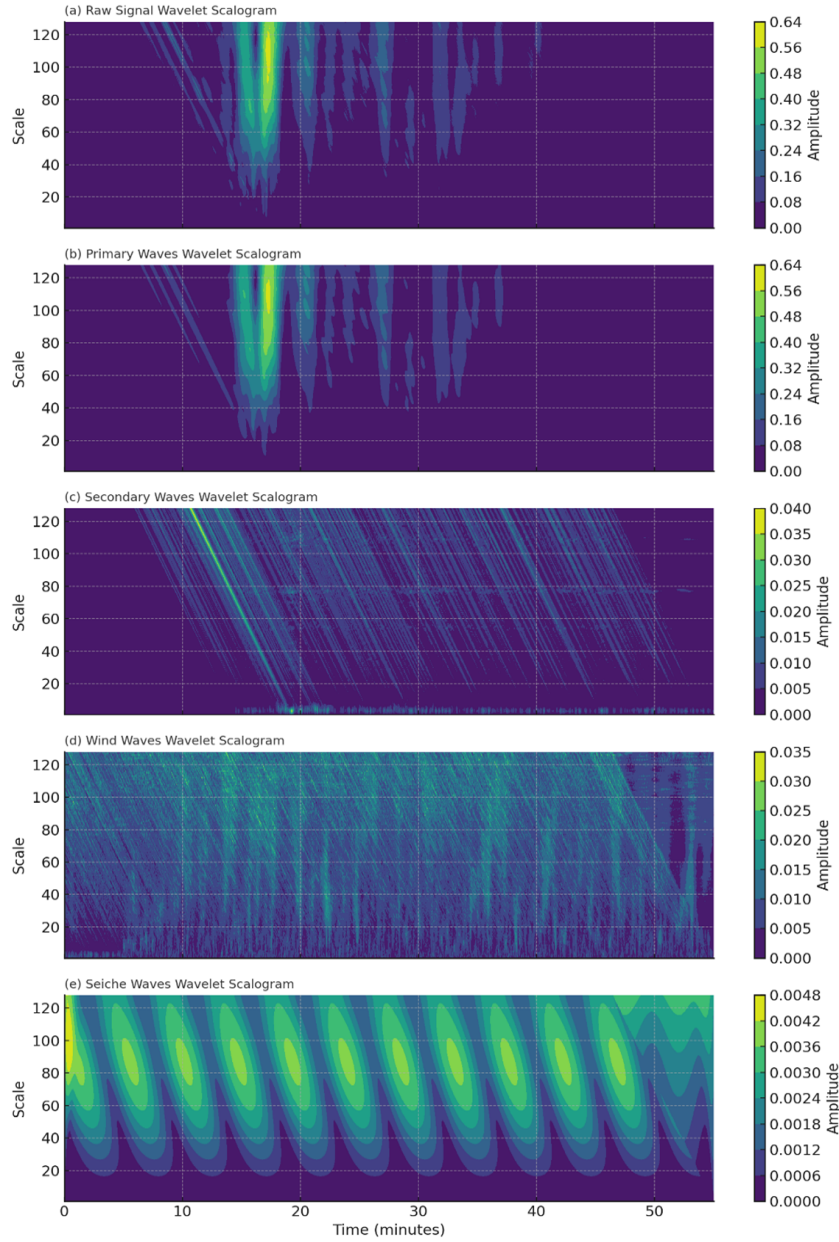


Fig. 21 Wavelet scalograms from the ship-generated wave event recorded at logger N1 on September 10, 2023. (a) Combined frequency distribution of all wave components. (b) Low-frequency, high-energy primary ship-generated waves. (c) High-frequency, short-duration secondary ship-generated waves. (d) Low-energy wind-driven waves. (e) Periodic low-frequency oscillations of seiche waves.

4.4.7 Normalized Energy Distribution

Figure 22 shows the normalized energy distribution of the raw signal, primary, secondary, wind, and seiche waves across varying frequencies. By normalizing the data, the relative energy contributions of each wave component are directly comparable, showcasing their unique frequency-dependent traits. Seiche waves dominate at low frequencies, wind waves contribute primarily at intermediate frequencies, and secondary waves peak in the high-frequency range. Primary waves, by contrast, span low-to-intermediate frequencies, reflecting their drawdown characteristics. This analysis underscores the success of the wave separation process and highlights the distinct contributions of ship-induced and natural waves.

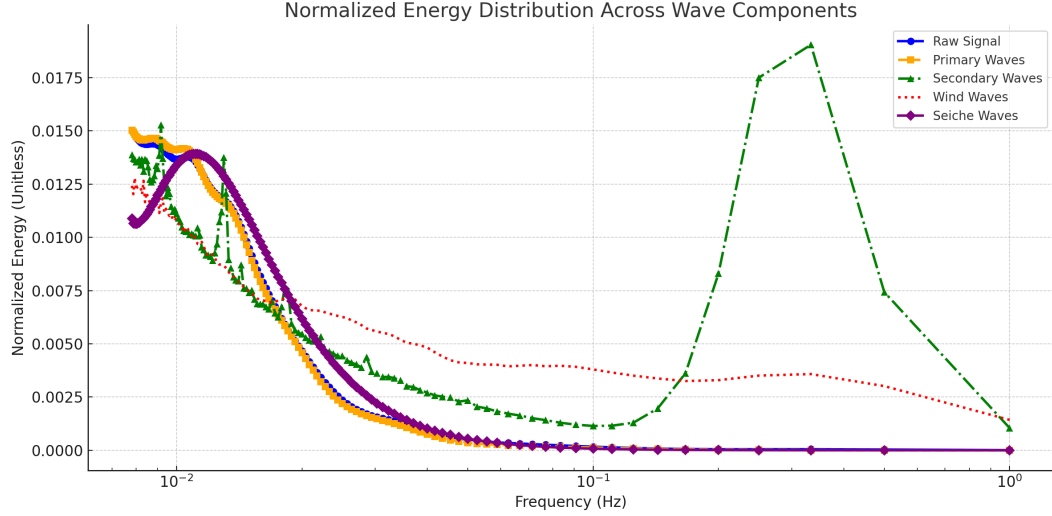


Fig. 22 Normalized energy distribution of wave components (raw signal, primary waves, secondary waves, wind waves, and seiche waves) as a function of frequency (Hz) from the ship-generated wave event recorded at logger N1 on September 10, 2023.

4.4.8 Site-Specific Comparison of Turbidity and Wave Components

The wave separation results provided a foundation for further investigation into the recorded data across each logger, enabling an analysis of location-specific wave characteristics for similar events at both locations. By isolating wind waves and ship-generated wave components, this approach allows for detailed comparisons of wave dynamics and turbidity responses at different logger sites, each positioned under unique environmental conditions.

Figures 23 and 24 present separated wave data from loggers N1 through N6, illustrating turbidity levels, wind wave heights, and ship-generated wave patterns. The top row of each figure shows turbidity (measured in NTU), which reflects sediment resuspension; the middle row displays wind wave heights, and the bottom row shows isolated ship-generated wave patterns for each location. These figures collectively capture each logger's unique wave and turbidity responses during a specific ship passage event. Although not shown here,

timestamps for the passage differ between sites due to the distance between the two study areas.

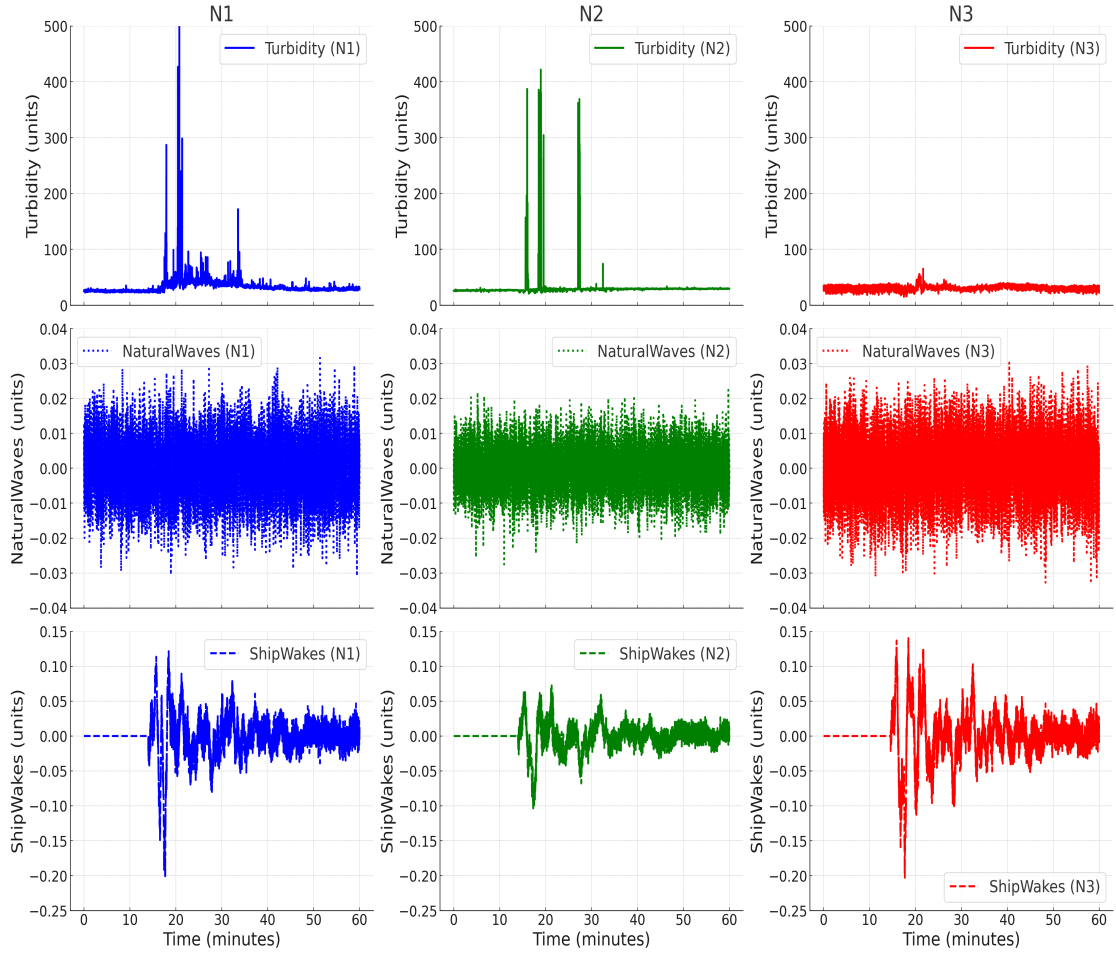


Fig. 23 Ship passage event at Mariatown on September 10, 2023, recorded by loggers N1, N2, and N3.

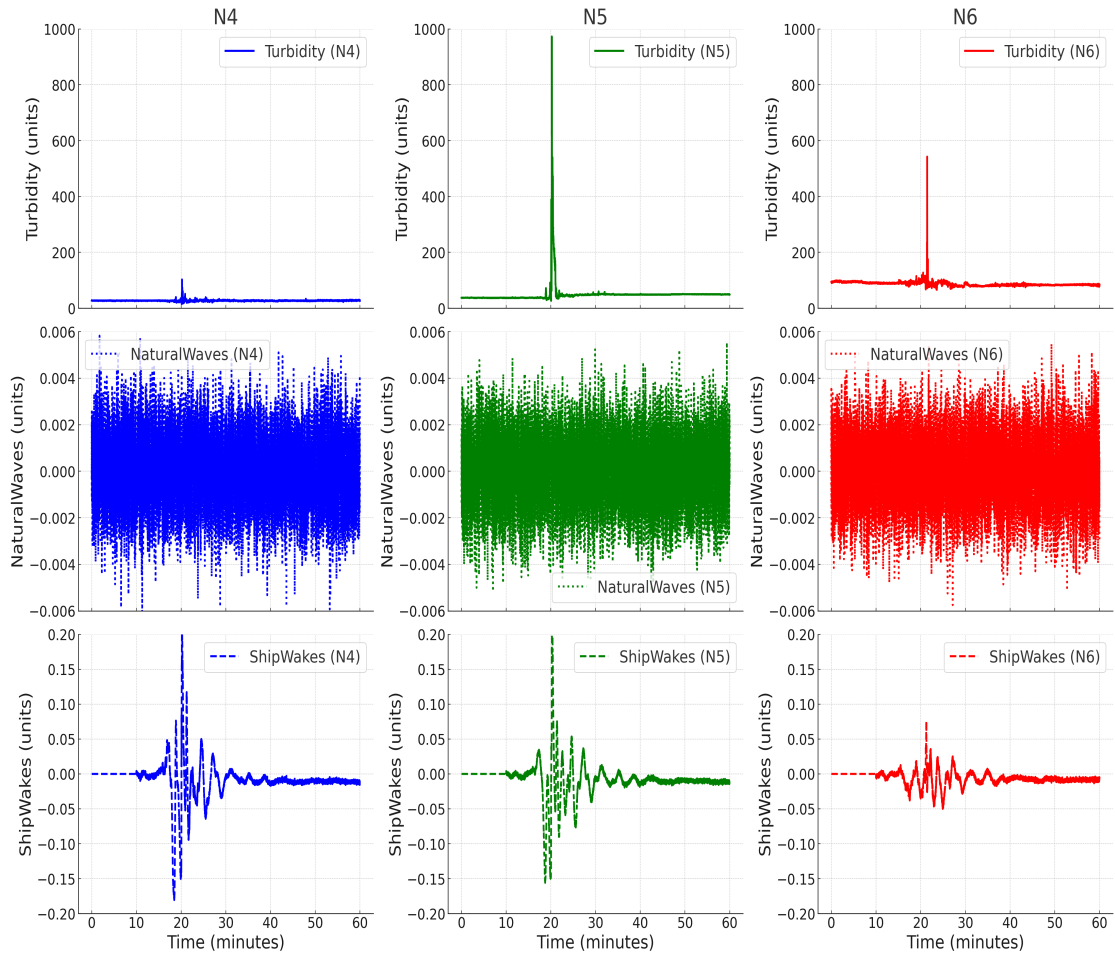


Fig. 24 Ship passage event at Jacobs Island on September 10, 2023, recorded by loggers N4, N5, and N6.

The comparative analysis of wave behavior and turbidity variations between the monitoring sites at Mariatown and Jacobs Island reveals distinct differences shaped by each location’s environmental characteristics and relative positions to the shipping lane (Table 9).

Table 9 Maximum and average turbidity and maximum natural wave and ship-generated wave height values for loggers N1 to N6 for the ship passage event on September 10, 2023.

Logger	Max Turbidity (NTU)	Avg Turbidity (NTU)	Max Natural Waves (m)	Max ship-generated waves (m)
N1	498.967	32.792	0.0316	0.1214
N2	421.884	31.122	0.0224	0.0724
N3	65.373	31.038	0.0302	0.1403
N4	102.792	26.984	0.0058	0.2692
N5	973.092	48.619	0.0055	0.2499
N6	542.764	86.887	0.0055	0.0761

At Mariatown, loggers N1, N2, and N3 each demonstrate unique turbidity and wave patterns influenced by their specific placements and depths. Logger N1, positioned in shallow water close to the shoreline, shows high turbidity peaks and is particularly sensitive to wind-generated waves and ship-generated waves. This sensitivity is attributed to the shallow depth and the fine sediment bed, which leads to greater sediment resuspension upon wave impact. Logger N2, situated farther offshore in deeper waters, still registers turbidity spikes and ship-generated wave effects, though with reduced intensity compared to N1. Its location at a greater depth helps to moderate the waves’ interaction with the river bed. Meanwhile, logger N3, located toward the center of the bay, presents an intermediate response in terms of turbidity and wave activity, influenced by a combination of wind and ship wave impacts, though less intensely than at N1.

In contrast, data from the loggers at Jacobs Island—N4, N5, and N6—display different patterns, with variations influenced by proximity to the shipping lane and the nature of the sediment bed. N4 and N5, placed on the eastern side near the shipping lane, experience strong ship-generated wave impacts, marked by notable turbidity peaks. Although a jetty partially shields N5, it remains exposed to east-west ship-generated waves and lies on a fine sediment bed, making it primarily reactive to vessel disturbances. N6, situated on the southern side of Jacobs Island and further from direct ship activity, shows much lower turbidity levels and wave response, primarily reflecting wind wave impacts with minimal ship-generated wave interference. This relative protection from the shipping lane contrasts the more exposed loggers at both Mariatown and the eastern side of Jacobs Island.

These findings emphasize that variations in depth, sediment type, and exposure to the shipping lane distinctly shape turbidity and wave patterns across the sites. They offer valuable insights into how localized environmental conditions directly influence sediment resuspension along the shoreline.

Table 10 overviews how wind waves and ship-generated waves contribute to turbidity and suspended sediment concentration (SSC) at various monitoring sites along the St. Lawrence

River. For each logger, the table presents average maximum (peak) and average mean turbidity levels associated with ship-generated waves, average mean turbidity from wind waves, and corresponding SSC for the average mean values.

Table 10 Average Turbidity and Suspended Sediment Concentration (SSC) for ship-generated waves and Wind Waves across all recorded events for each logger.

Logger	Avg Peak Turbidity from ship-generated wave (NTU)	Avg Mean Turbidity from ship-generated wave (NTU)	Avg Mean Turbidity from Wind Waves (NTU)	Avg SSC from ship-generated wave (g/L)	Avg SSC from Wind Waves (g/L)
N1	384.7	35.6	29.2	0.030	0.017
N2	336.4	24.7	21.1	0.009	0.002
N3	56.2	29.4	26.3	0.018	0.012
N4	91.8	28.9	23.7	0.017	0.007
N5	748.7	45.1	37.2	0.048	0.033
N6	423.4	72.3	69.8	0.101	0.096

The turbidity and SSC measurements in Table 10 are averages calculated over the entire deployment period. The wind values capture a broad spectrum of wind events typical of this area, and thus establish a representative baseline for turbidity and SSC resulting from wind waves by accounting for a range of wind conditions. SSC contributions from wind waves were notably consistent, with values ranging from 0.0016 g/L at N2 to 0.0964 g/L at N6, and were greater in shallower areas where continuous wave action perpetuates sediment resuspension. In contrast, ship-generated waves lead to short-lived but intense turbidity spikes, reflected in ship-generated wave-induced mean SSC values such as 0.0484 g/L at N5 and 0.1013 g/L at N6. These effects were transient, typically returning to baseline about 40 minutes after a ship passed.

The data underscore the role of wind waves in establishing a stable, persistent turbidity baseline, particularly in shallow areas with fine sediment. This continuous influence of natural wave action results in sustained sediment resuspension. Conversely, ship-generated waves cause substantial, immediate turbidity peaks, as seen at loggers near the shipping lane like N4 and N5, where peak turbidity values were on average 748.7 NTU at N5. Despite their intensity, these peaks are temporary, with turbidity levels returning to baseline relatively quickly, highlighting the episodic nature of ship-generated wave impacts.

This final section summarizes the cumulative impact of ship-generated waves and wind waves on sediment resuspension and turbidity at each logger site. Using Table 8's data on ship passages and SSC values from Table 10, SSC specifically generated by ship-generated waves was isolated by subtracting baseline wind wave SSC from post-ship-passage SSC values. Thus, SSC contributions from ship-generated waves appear as incremental increases above wind wave baseline values. This approach highlights the additional sediment resuspension induced by ship-generated wave events. Ship-generated waves were estimated to affect resuspension over 40-minute intervals for each ship passage event in the study period, while wind waves provided a continuous baseline at each logger. Figure 25 visualizes this site-specific comparison, illustrating each wave type's distinct role in sediment dynamics.

Shallow loggers near the shipping lane, such as N4 and N5, show substantial SSC contributions from ship-generated waves due to greater vessel traffic exposure. Meanwhile, sites like N6, farther from the channel, exhibit more influence from wind waves, indicating ongoing natural sediment resuspension.

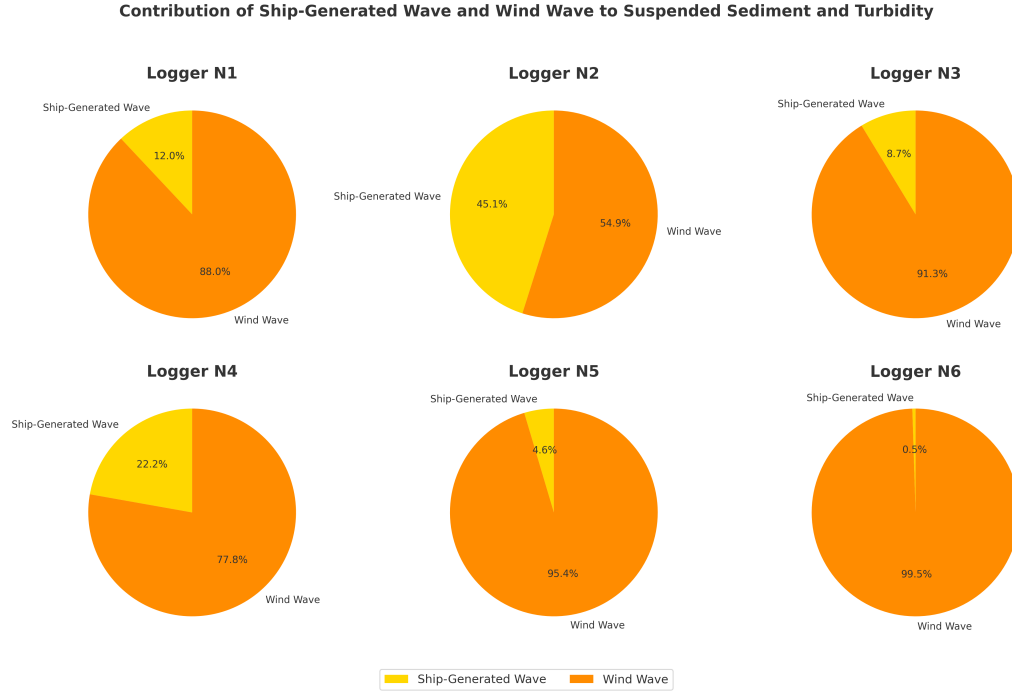


Fig. 25 Contribution of ship-generated waves and wind waves to suspended sediment concentration (SSC) and turbidity across six logger sites (N1–N6).

While the separation of wind- and ship-induced SSC was achieved through spectral analysis and pre-event baseline subtraction, it is important to note that the turbidity-to-SSC conversion used in this study was based on a site-specific linear calibration obtained through sediment sampling. This approach assumes a relatively stable particle-size distribution and consistent turbidity sensor performance throughout the monitoring period. Although suitable for comparative assessments across logger sites and event types, this method does not account for temporal variability in sediment composition or potential sensor drift. Future work may benefit from incorporating formal uncertainty analysis or sensitivity testing to improve accuracy. Additionally, the persistent SSC levels associated with wind wave activity—especially at shallow, unprotected sites such as logger N6—may lead to gradual but continuous sediment remobilization and contribute to long-term shoreline retreat. This observation aligns with earlier findings in this study’s shoreline analysis and is consistent with prior work on chronic wind-induced resuspension in riverine and estuarine systems [55, 112]. While ship-generated waves produce short-lived but intense sediment disturbances,

wind waves exert a more sustained influence on nearshore sediment dynamics, underscoring the combined effect of natural and anthropogenic drivers on erosion processes.

This simplified approach clarifies the contrast between ship-generated waves' episodic, high-intensity effects and wind waves' consistent, lower-impact influence. By isolating ship-generated wave SSC as an additional contribution, this analysis underscores the combined role of human activity and natural forces in shaping shoreline sediment dynamics. These insights are crucial for site-specific shoreline management and sediment control strategies.

4.5 Conclusion

This study provided a detailed field-based analysis of wave-induced sediment dynamics along a 55 km stretch of the upper St. Lawrence River, covering sites from Mariatown to Jacobs Island. The research investigated how ship-generated waves and natural wind waves influence turbidity and suspended sediment concentration (SSC), with a focus on short-term sediment resuspension processes observed across multiple logger locations.

The results demonstrate that wind waves establish a persistent turbidity baseline, particularly at shallow, unprotected sites, whereas ship-generated waves produce intense but short-lived turbidity and SSC spikes. The magnitude and duration of these responses vary by logger site, with turbidity peaks reaching up to 973NTU and corresponding SSC levels exceeding 0.1g/L in some cases.

A targeted methodology was developed to separate wave components using synthetic signal modeling, frequency filtering, and spectral subtraction. This approach effectively addressed limitations of conventional wavelet-based separation in real-world, noisy datasets. Wavelet scalograms were used as a validation tool to confirm the spectral localization of primary and secondary wave components. The method supports multi-event processing and accommodates variable environmental conditions, making it suitable for large-scale deployments.

While shoreline change was not formally analyzed in this study, the observed differences in turbidity and SSC among logger sites provide a framework for evaluating localized sediment responses under different wave regimes. The approach outlined here may inform future research on riverine sediment transport and shoreline processes by offering a replicable framework for isolating wave contributions to sediment resuspension in regulated waterways.

5 Impact of Ship Characteristics on Wave Dynamics and Sediment Resuspension in the Upper St. Lawrence River: A Field Data Analysis

5.1 Abstract

This study investigates the influence of ship-generated waves on sediment resuspension in the Upper St. Lawrence River, combining empirical analysis and machine learning. Building on previous field investigations, it quantifies how vessel speed, draft, length, and hull type affect nearshore wave energy, shear stress, and turbidity generated by sediment resuspension.

Time-delayed multivariate regression and Long Short-Term Memory (LSTM) neural networks were applied to 2 Hz sampling-frequency wave and vessel datasets to evaluate both instantaneous and cumulative impacts. Higher vessel speeds were associated with increased primary wave energy, while deeper drafts elevated near-bed shear stress and turbidity, particularly in shallow areas with fine sediments. Regression models captured direct relationships, and the LSTM framework resolved nonlinear dependencies across sequential events.

Findings identify operational conditions that intensify sediment resuspension and provide a basis for predictive risk assessment. The combined modeling approach supports management interventions such as speed regulation, schedule optimization, and hull design improvements aimed at mitigating ecological impacts while maintaining navigational efficiency.

Limitations include the seasonal scope of field data and exclusion of wind forcing and discharge variability, indicating areas for future enhancement. Overall, the study contributes a robust, data-driven framework for managing sediment dynamics in high-traffic riverine systems.

5.2 Introduction

High-traffic waterways such as the upper St. Lawrence River in Canada, increasingly experience anthropogenic disturbances, particularly those related to commercial vessel activity. Among these disturbances, vessel-generated waves are prominent drivers of sediment resuspension, shoreline erosion, and habitat disruption [53, 77, 123, 134]. Ship-generated waves mobilize sediments from riverbeds, elevating turbidity and modifying sediment transport dynamics, significantly impacting water quality and ecosystem health [33, 135–137].

Recent field investigations by Haghighi et al. (2025a) identified vessel-induced turbidity spikes, distinguishing primary and secondary wave components from natural wave processes [11]. Although highlighting the differential roles of these wave types in sediment resuspension, that study did not quantify the hydrodynamic forces (energy and shear stress) of individual wave components or model their cumulative impacts over time.

Ship-generated wave characteristics depend on vessel-specific parameters including speed, draft, length, and hull form [18, 129, 136, 138]. Vessel speed, often used to calculate the vessel Froude number (Fr), significantly influences wave formation, distinguishing between subcritical, critical, and supercritical flow conditions. Increased speeds result in higher wave energy, notably exacerbating sediment mobilization [18, 129, 136]. Macfarlane et al. (2019) reported that elevated vessel speeds could amplify wave heights by up to 80% and extend wave periods by 30% [18]. Additionally, nonlinear wave phenomena (e.g., Korteweg-de Vries

solitons), occurring when Fr number exceeds 0.5, further intensify sediment displacement [136, 139]. High-speed vessels in constrained waterways can generate substantial waves, significantly affecting nearshore turbidity [54, 138, 140].

Beyond its speed, vessel length, draft, and hull geometry also critically influence wave generation and impacts. Larger vessels sustain hydrodynamic disturbances longer, thus increasing associated turbidity and erosion risks [23, 116]. Deep-draft vessels, particularly those with high draft-to-depth ratios, intensify near-bed orbital velocities, elevating shear stresses and enhancing sediment resuspension [84, 116, 135, 136]. Hull geometry further determines wave patterns, with different vessel designs (e.g., monohull, catamaran) altering wave duration and spatial influence [34, 136, 140].

Despite prior advances, knowledge gaps persist regarding the combined and cumulative effects of vessel characteristics on sediment dynamics, particularly in confined river systems. Existing mitigation measures, such as speed limits, rarely account for vessel geometry and cumulative wave impacts. Previous studies, including Haghighi et al. (2025a), predominantly analyzed turbidity responses without explicitly quantifying the contributions of primary and secondary waves to shear stress and sediment transport processes.

Addressing these gaps, this study quantitatively evaluates wave-induced wave energy and near-bed shear stress associated with various vessel parameters. Utilizing both time-delayed regression and innovative Recurrent Neural Network - Long Short-Term Memory (RNN-LSTM) modeling approaches, this research explicitly quantifies immediate and cumulative impacts on turbidity and shear stress from sequential ship passages. By clearly establishing mechanistic relationships between vessel characteristics and sediment resuspension, the outcomes provide practical insights to guide effective shoreline management and sediment mitigation strategies in high-traffic waterway environments.

5.3 Methodology

This study builds upon the dataset and findings reported by Haghighi et al. (2025a), which involved a detailed field investigation and spectral analysis of ship-generated wave impacts on sediment resuspension in the Upper St. Lawrence River. The dataset includes 2 Hz sampling frequency measurements of wave heights and turbidity collected from two instrumented locations along the river. In the above mentioned study, ship-generated waves were distinguished from natural wave events through spectral analysis and validated using vessel passage information obtained from the Enhanced Maritime Situational Awareness (EMSA) system. Primary and secondary wave components were identified for each vessel passage event. Wave component validation was further supported using continuous wavelet transform (CWT) analysis to confirm the frequency and duration characteristics.

In the present study, additional data processing was undertaken to improve wave event identification and quantify wave-induced hydrodynamic forces and their potential to resuspend sediment. The dataset was reanalyzed to determine the number of vessel passages, categorized by vessel type, as recorded by the nearshore loggers. Details of the logger deployment locations (sites N1–N6) and regional bathymetry are available in Haghighi et al. (2025a, Table 1 and Fig. 2) [11]. Among the six deployed loggers, stations N1 and N4, respectively located at the most exposed nearshore positions, at the Mariatown and Jacob’s Island study sites, were selected for detailed analysis due to their higher sensitivity to wave events.

Each wave event was identified by aligning vessel arrival times from EMSA with peaks observed in wave height and turbidity records. In cases where EMSA data were incomplete or inconclusive, supplementary camera footage was used to verify vessel passages. Vessel attributes relevant to wave generation, including type, length, speed, draft, and hull form, were compiled from EMSA logs and field observations, as shown in Table 11.

Table 11 Vessel Types and Characteristics

Vessel Type	Length (m)	Avg Speed (m/s)	Avg Draft (m)	Hull Type
Barge	80–200	3.1–5.1	3–6	Displacement (Monohull)
Cargo	100–225	4.1–6.2	6–8.2	Displacement (Monohull)
Tanker	150–225	4.6–6.2	7–8.6	Displacement (Monohull)
Others	10–100	4.1–6.7	1–7	Monohull, Catamaran, or Planing Hull

For each identified wave event, the root mean square (RMS) wave height, H_{rms} , was calculated for both primary and secondary wave components. The corresponding wave energy, E , was estimated using the equation:

$$E = \frac{1}{8} \rho g H_{\text{rms}}^2, \quad (25)$$

where $\rho = 1000 \text{ kg m}^{-3}$ is the water density and $g = 9.81 \text{ m s}^{-2}$ is gravitational acceleration. An empirical correction for shallow water conditions (depth $< 2 \text{ m}$) was inherently incorporated through the use of linear wave theory, which captures the amplification of near-bed orbital velocities in shallow environments. Specifically, the near-bed orbital velocity (u_b) was estimated using:

$$u_b = \frac{\pi H}{T \sinh(kh)}, \quad (26)$$

where H is wave height, T is wave period, h is local water depth, and k is the wave number derived from the dispersion relation. In shallow water, the term $\sinh(kh)$ becomes small, significantly increasing u_b and thus the estimated bottom shear stress. No additional correction factor was required, as the formulation itself captures this depth-sensitive enhancement (Dean & Dalrymple, 1991) [9].

Near-bed orbital velocity (U_b) was estimated at stations N1 and N4 based on wave height, period, and local depth measurements. Acoustic Doppler Current Profiler (ADCP) data confirmed that background current velocities were negligible at these locations, indicating that wave forcing was the primary mechanism for sediment resuspension.

Wave-induced shear stress, τ_w , was computed as:

$$\tau_w = \frac{1}{2} \rho f_w U_b^2, \quad (27)$$

where f_w is the wave friction factor, assigned based on bed type. Friction factors were adopted from the site-specific bed characterization reported in Haghighi et al. (2025a). Sandy substrates (stations N1, N2, N3, and N5) were assigned lower roughness coefficients

($f_w = 0.025$), while rocky substrates (stations N4 and N6) were assigned higher values ($f_w = 0.040$). These values reflect empirically established ranges for fine to medium sandy beds and coarse rocky substrates, consistent with Soulsby (1997) and Nielsen (1992) [7, 10], and are aligned with site-specific observations reported in Haghighi et al. (2025a) [11].

The calculated shear stress values were compared with the corresponding turbidity peaks (T_{peak}) to evaluate the relationship between wave-induced forces and sediment resuspension at the nearshore locations.

The influence of vessel speed and hull form on wave dynamics was analyzed using Froude number (F_r) calculations:

$$F_r = \frac{V}{\sqrt{gL}}, \quad (28)$$

where V (m/s) is the vessel speed, L (m) is the vessel length, and g is the gravitational acceleration. Based on established criteria from naval hydrodynamics literature [37, 141], vessels were classified into three wave regimes:

- Subcritical: $F_r < 0.4$
- Transcritical: $0.4 \leq F_r \leq 0.5$
- Supercritical: $F_r > 0.5$

To validate these thresholds, k-means clustering was applied to F_r values, identifying empirical breakpoints at approximately $F_r = 0.378$ and $F_r = 0.489$. These thresholds closely matched the conventional classifications and were adopted for consistency.

A time-delayed multiple linear regression model was developed to evaluate the combined effects of the scaled wave parameters on turbidity and shear stress. To account for potential time-lagged responses in sediment resuspension, a time delay was incorporated into the model.

The response variable, Y (i.e., turbidity), was modeled as:

$$Y = \beta_0 + \beta_1 H_{\text{rms}} + \beta_2 E + \beta_3 \tau_w + \beta_4 U_b + \beta_5 \Delta t + \epsilon, \quad (29)$$

where Δt represents the time lag between the initial wave impact and the peak sediment response, and ϵ is the error term. The regression coefficients (β_i) describe the relative influence of each parameter on sediment resuspension outcomes. The model was developed using ship-passage forcing parameters and subsequently validated against logger-derived data [11]. This validation ensured that the reported performance statistics reflected predictive skill rather than in-sample fit.

In addition to the regression analysis, a bidirectional Long Short-Term Memory (LSTM) neural network was implemented to predict sequential wave-induced variations in bed shear stress and turbidity. The model used an expanded dataset consisting of 14 standardized input variables (Table 12), with shear stress and maximum turbidity spike as the target outputs.

The dataset was divided into training (80%) and testing (20%) subsets using stratified random sampling to preserve the variability in the data. The LSTM model architecture included two stacked bidirectional LSTM layers. The first layer had 64 units with return_sequences enabled, while the second layer had 32 units. Each LSTM layer was followed by batch normalization and dropout (rate = 0.2). A dense layer with 16 neurons and ReLU activation preceded the final output layer, which included two neurons corresponding to the target variables.

The model was compiled using the AdamW optimizer with a learning rate of 0.001. Huber loss [142] was used as the objective function due to its robustness to outliers, which are common in environmental datasets. The model was trained for 50 epochs with a batch size of 32. Early stopping was applied, with training halted if validation loss did not improve for five consecutive epochs, to prevent overfitting and enhance model generalization.

Model performance was evaluated using Mean Absolute Error (MAE) and Huber loss on the test set. Additional validation included comparisons of observed and predicted values, as well as analysis of error distributions.

Table 12 Scaled Input Variables Used in LSTM Model, N1 station

Variable	Description
Vessel Speed	EMSA-derived passage speed
Vessel Length	Waterline length
Draft	Vertical distance from waterline to keel
Primary Wave Height	RMS of primary wave component
Secondary Wave Height	RMS of secondary wave component
Primary Wave Energy	Calculated from H_{rms}
Secondary Wave Energy	Calculated from H_{rms}
Orbital Velocity	Estimated near-bed wave orbital velocity
Bed Pressure Gradient	Derived from wave energy and depth
Drawdown Velocity	Flow velocity induced by vessel passage
Lag Shear Stress	Time-lagged bed shear stress
Lag Turbidity	Time-lagged turbidity
Lag Wave Energy	Time-lagged wave energy
Froude Number	Ratio of vessel speed to gravity wave speed

All data processing tasks, including signal filtering, wave energy calculations, regression analysis, and neural network model training, were developed in Python. The workflow utilized libraries such as NumPy, SciPy, scikit-learn, and TensorFlow. All code was version-controlled using Git, and the entire analysis pipeline was automated to facilitate reproducibility and enable scenario testing under different vessel operation profiles.

5.4 Results

The results of this study provide a detailed evaluation of vessel traffic characteristics, wave-induced shear stress, wave energy partitioning, and model-based predictions of sediment resuspension processes. These findings contribute to a process-based understanding of how ship-generated waves influence hydrodynamic forcing and turbidity in the Upper St. Lawrence River, Canada.

A total of 2,559 vessel passages were documented between 2022 and 2023. These were classified by direction (upstream bound and downstream bound) and vessel type (barge, cargo, tanker, and other), using records from Seaway traffic reports and validated against Enhanced Maritime Situational Awareness (EMSA) logs [2, 3]. Cargo vessels accounted for the highest frequency of passages, particularly in confined, shallow reaches where repeated events occurred within short time intervals (Figure 26).

Froude numbers (F_r) were computed based on vessel speed and length for each vessel type. All vessels operated under subcritical flow conditions ($F_r < 0.4$), as summarized in Table 13. While cargo and tanker vessels exhibited similar F_r values (0.11–0.12), smaller

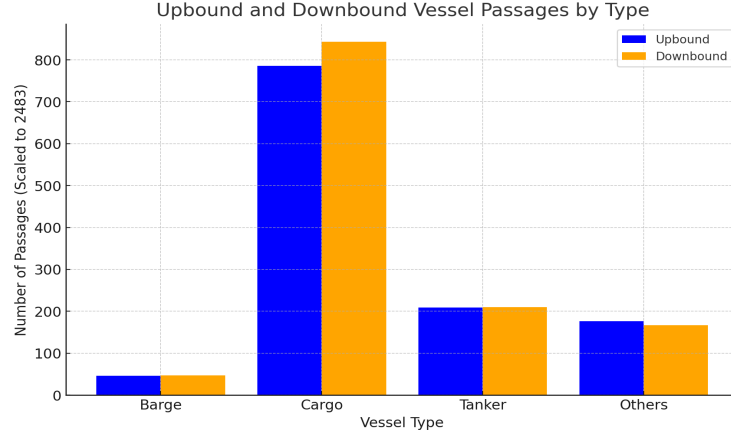


Fig. 26 Distribution of recorded vessel passages by direction and type [2, 3].

vessels in the "Others" category reached values as high as 0.25, indicating faster movement relative to their length and increased potential for nonlinear wave interactions.

Table 13 Froude Number Classification by Vessel Type

Vessel Type	Avg Length (m)	Avg Speed (m/s)	Froude Number	Fr Category
Barge	140.0	4.12	0.11	Subcritical
Cargo	162.5	4.63	0.12	Subcritical
Tanker	187.5	4.63	0.11	Subcritical
Others	55.0	5.92	0.25	Subcritical

Wave-induced near-bed shear stress (τ_w) showed considerable variation by vessel type and monitoring location. At station N1 (Figure 27), tanker passages resulted in the highest mean τ_w values, exceeding 0.15 N/m^2 , followed by cargo ships (0.13 N/m^2) and barges (0.06 N/m^2). In contrast, station N4 (Figure 28), characterized by coarser substrate and greater depth, showed lower stress values across all vessel types, with tankers inducing a maximum shear stress of approximately 0.08 N/m^2 . The spatial variability across stations N1–N6 is summarized in Figure 29.

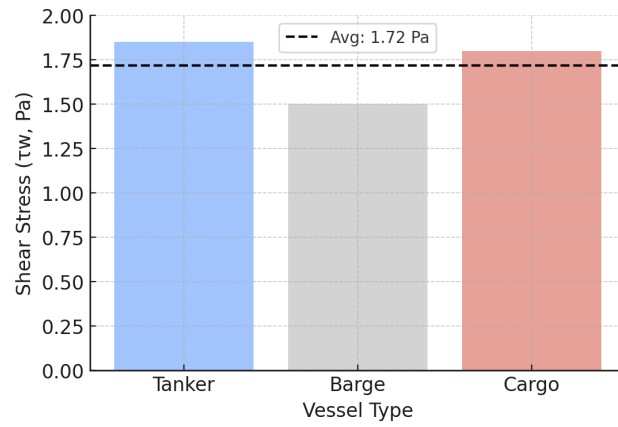


Fig. 27 Average wave-induced shear stress (τ_w) at station N1 by vessel type.

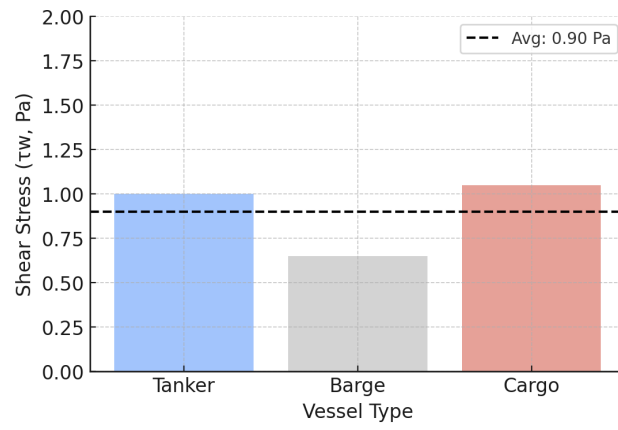


Fig. 28 Average wave-induced shear stress (τ_w) at station N4 by vessel type.

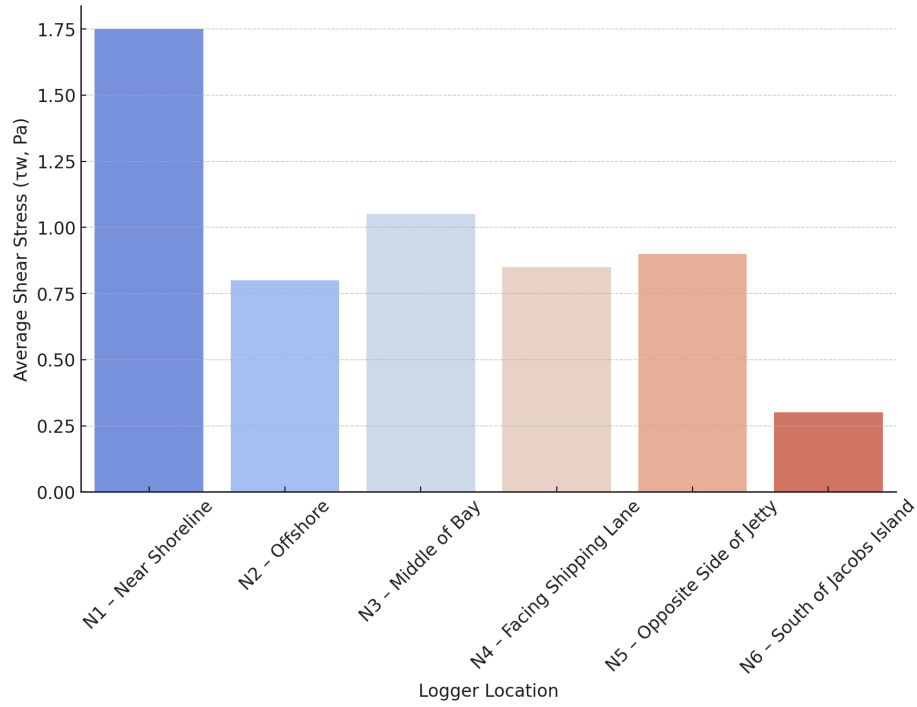


Fig. 29 Mean shear stress (τ_w) across monitoring stations N1–N6.

Primary wave energy consistently represented the dominant portion of total wave energy across all vessel types. Table 14 presents primary wave energy values at station N1.

Table 14 Primary Wave Energy Statistics at Station N1

Vessel Type	Primary Mean Wave Energy (J/m ²)	Std. Dev. (J/m ²)	Min (Mean – Std.)	Max (Mean + Std.)
Tankers	103	8.91	94.09	111.91
Barges	41	0.46	40.54	41.46
Cargo Ships	92	0.58	91.42	92.58

Tankers produced the highest mean energy (103 J/m²), with cargo vessels following closely (92 J/m²). Barges generated substantially lower values (41 J/m²). These trends are visually depicted in Figure 30, while Figure 31 illustrates the temporal decay of both primary and secondary wave components following each vessel passage.

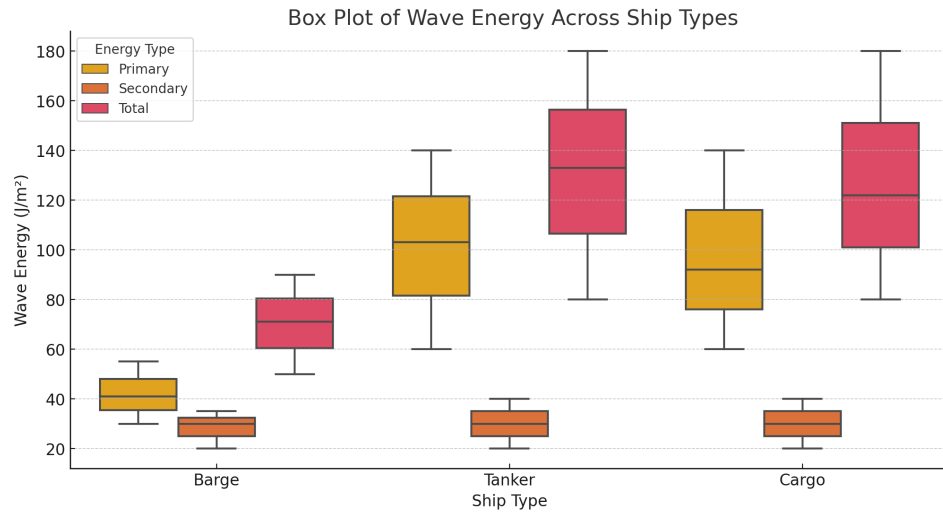


Fig. 30 Mean primary, secondary, and total wave energy by vessel type at station N1.

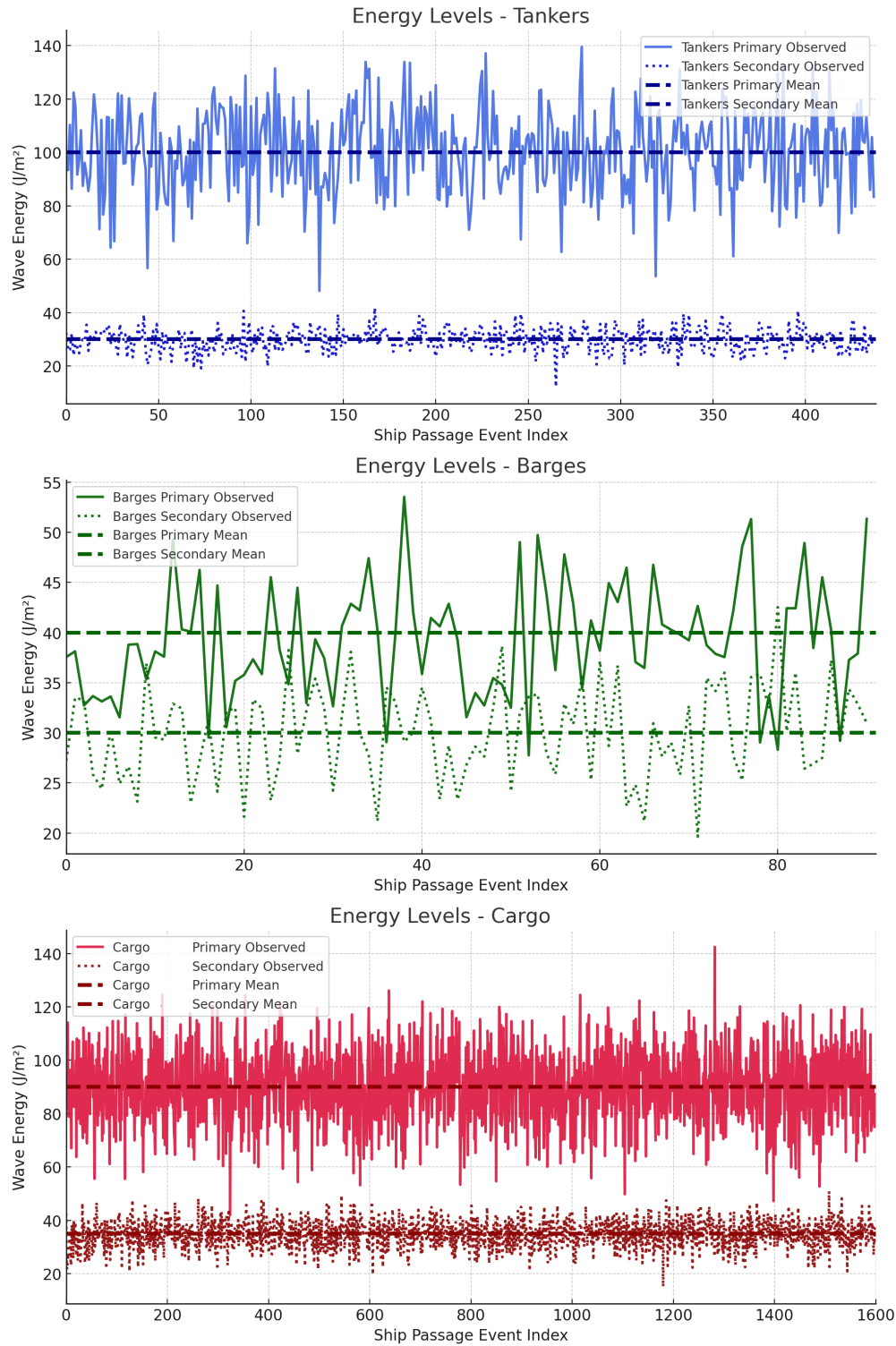


Fig. 31 Mean and observed primary, secondary, and total wave energy by vessel type for each passage recorded, at station N1.

A time-delayed multi-variable linear regression model was used to evaluate relationships between vessel parameters, wave characteristics, and measured nearshore responses (see Section 6.3, Equation 29). Inclusion of time lag terms allowed the model to account for delayed sediment responses to successive wave events. Across all vessel types, primary wave energy and vessel speed exhibited the strongest associations with peak turbidity and τ_w . Figures 33 to 37 illustrate model fits by vessel type and station. Cargo and tanker passages at station N1 yielded the highest model performance, with R^2 values exceeding 0.75 and normalized RMS errors of 19% for wave-induced shear stress and 22% for turbidity.

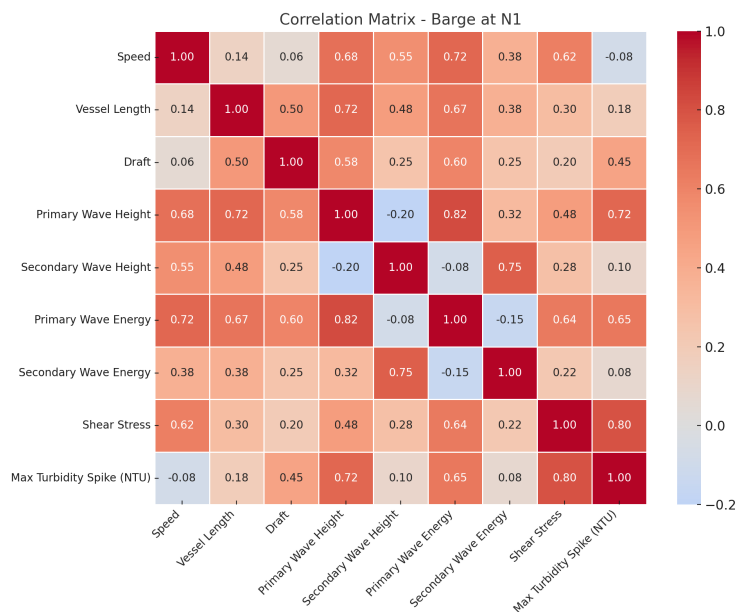


Fig. 32 Time-delayed multi-variable linear regression results for barge passages at station N1.

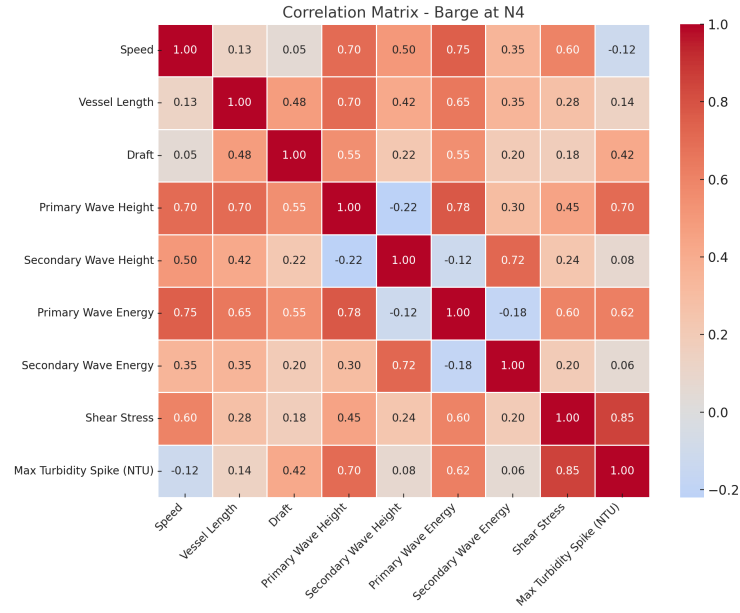


Fig. 33 Time-delayed multi-variable linear regression results for barge passages at station N4.

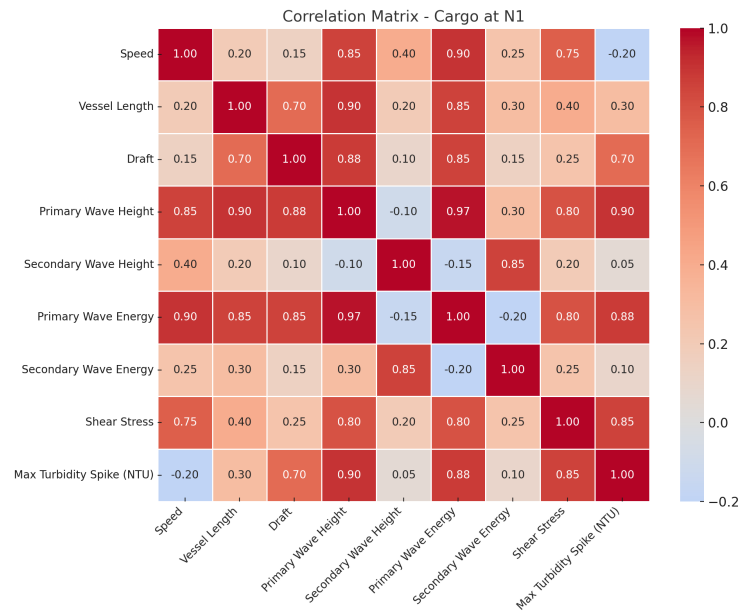


Fig. 34 Time-delayed multi-variable linear regression results for cargo passages at station N1.

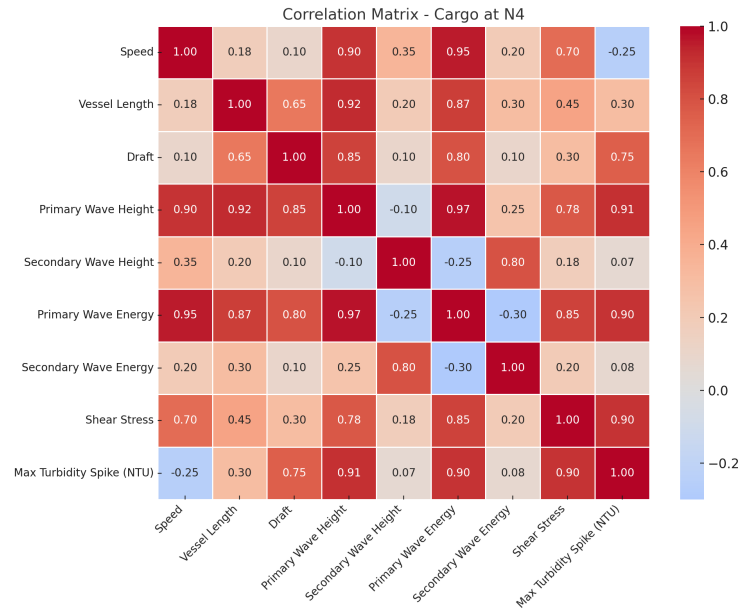


Fig. 35 Time-delayed multi-variable linear regression results for cargo passages at station N4.

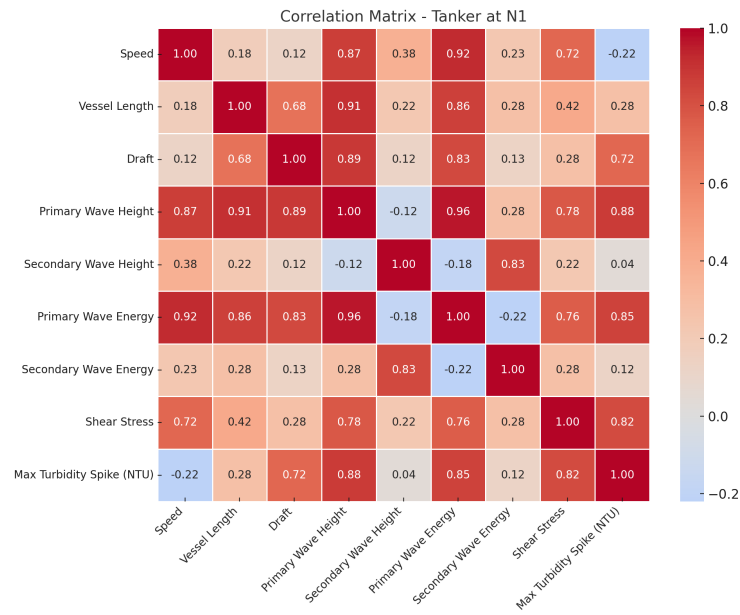


Fig. 36 Time-delayed multi-variable linear regression results for tanker passages at station N1.

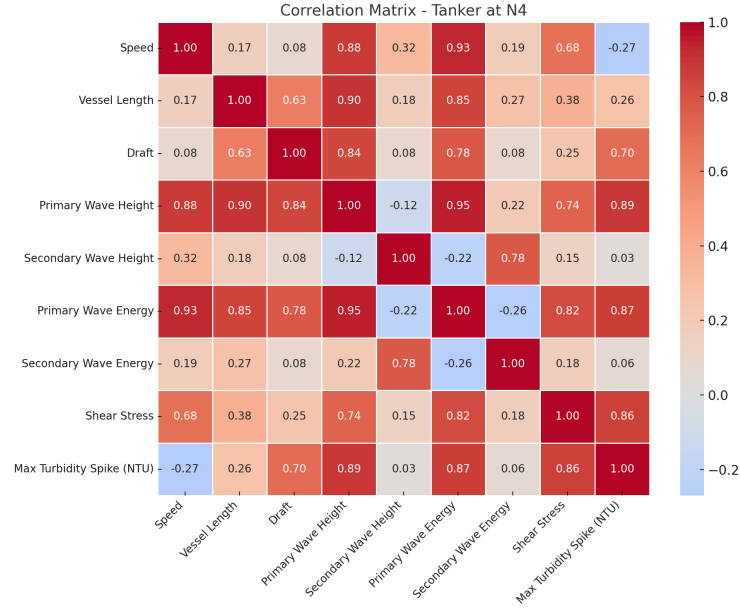


Fig. 37 Time-delayed multi-variable linear regression results for tanker passages at station N4.

The Long Short-Term Memory (LSTM) model was trained using the same feature set to predict τ_w and turbidity values. Model performance is summarized in Figures 38 through 41. The Huber loss curve (Figure 38) showed convergence around epoch 35, with validation loss closely following the training loss.

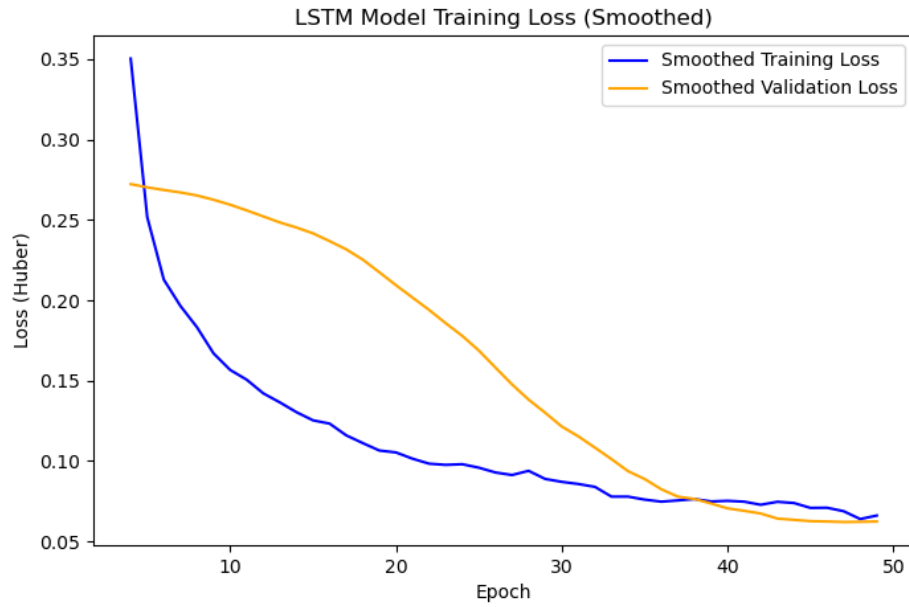


Fig. 38 Training and validation Huber loss for the LSTM model over 50 epochs.

Observed versus predicted outputs (Figure 39) aligned closely with measured values, particularly within the low-to-moderate range. Most predictions were within $\pm 15\%$ of observed outcomes.

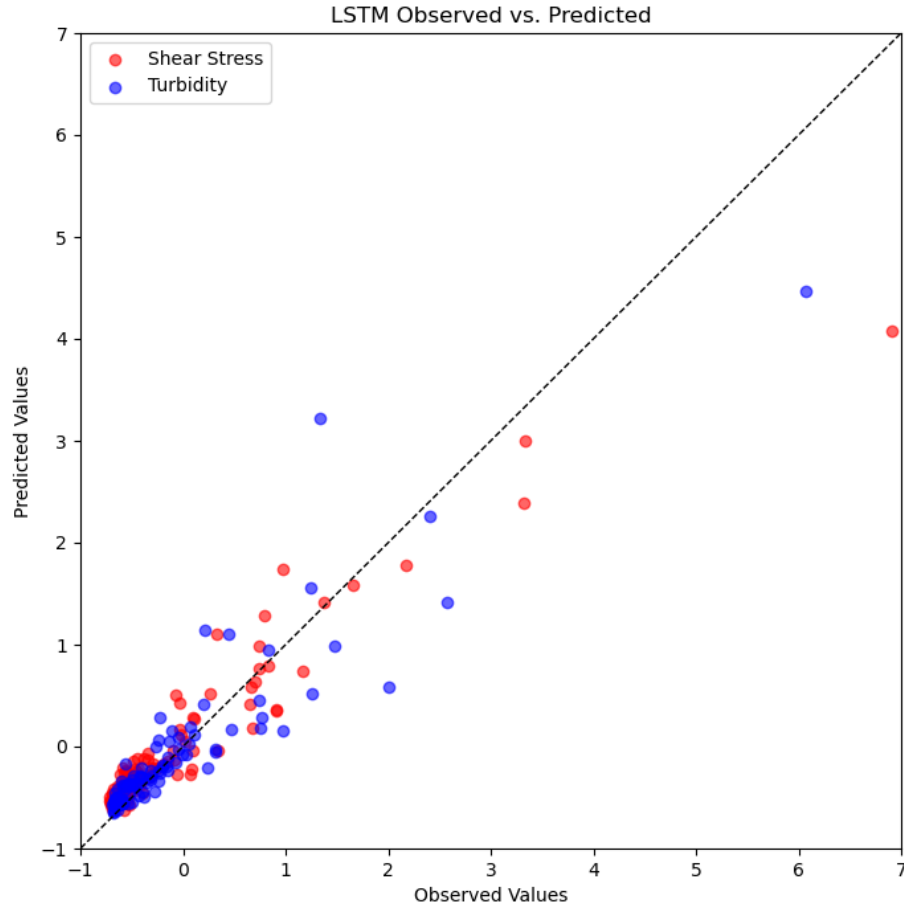


Fig. 39 Observed versus predicted turbidity (NTU) and wave-induced shear stress (N m^{-2}) from the LSTM model. All variables (inputs and target outputs) were standardized using zero-mean, unit-variance scaling, and predictions were inverse-transformed to physical units for comparison.

The error distribution (Figure 40) was symmetric and centered near zero, indicating minimal bias across both outputs.

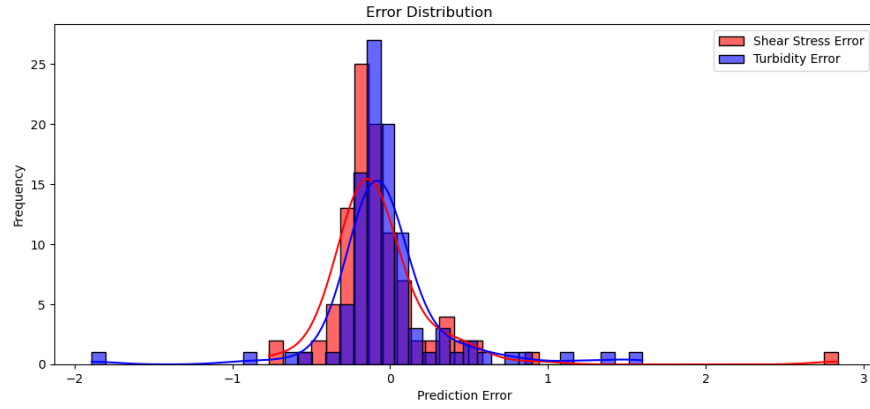


Fig. 40 Prediction error distribution for turbidity and shear stress.

Bed pressure gradient and orbital velocity ranked highest in feature importance (Figure 41) with respect to their influence on the LSTM model's accuracy in predicting near-bed shear stress and turbidity, followed by primary wave energy, vessel speed, and draft. Lagged shear stress and turbidity variables also had strong influence, confirming the contribution of residual energy and suspended sediments from previous vessel passages. The model showed decreased performance for isolated peak events, likely due to external drivers not included in the dataset (e.g., wind-induced mixing or bedform shifts).

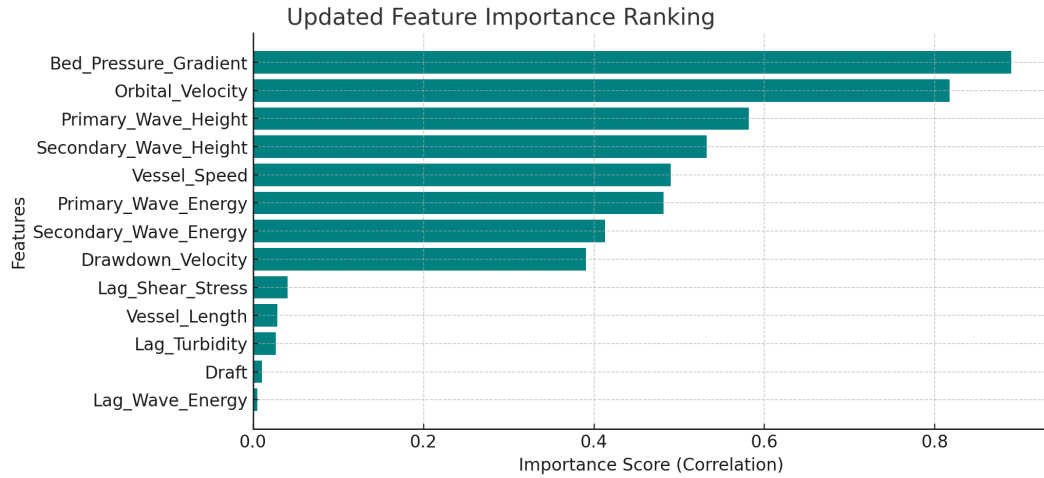


Fig. 41 Feature importance rankings from the LSTM model for predicting near-bed shear stress and turbidity.

The comparison presented in Table 15 summarizes the relative influence of all input factors on predicting near-bed shear stress (τ_w) and turbidity using the two modelling approaches. The observed differences arise primarily from the linear nature of the multiple regression model, which evaluates each factor independently on an event-by-event basis, treating every ship passage as an isolated observation with single-value inputs. In contrast, the LSTM model has access to the full temporal sequence of wave-sediment responses and can therefore capture nonlinear dependencies, cumulative effects from previous passages, and delayed sediment responses. As a result, regression highlights the dominant linear controls (e.g., primary wave energy and vessel speed), whereas LSTM assigns greater importance to dynamic variables such as bed pressure gradient, orbital velocity, and lagged terms that represent residual energy and suspended sediment.

Table 15 Comparison of factor importance for predicting τ_w and turbidity using regression and LSTM at station N1.

Factor	Regression	LSTM	Interpretation
Primary Wave Energy	High for both τ_w and Turbidity	High for τ_w ; Medium-High for Turbidity	Strong linear driver; LSTM moderates effect
Primary Wave Height (Hrms)	High influence on both outputs	High influence on both outputs	Correlates with energy; similar trend
Vessel Speed (V)	High for both outputs	Medium-High for both outputs	Dominant in regression; softened in LSTM
Draft	Medium-High for τ_w ; Medium for Turbidity	Medium-High for both	More important during high-energy events
Orbital Velocity	Medium	Very High for both outputs	One of the top LSTM predictors
Bed Pressure Gradient	Medium	Very High for both outputs	Highest importance in LSTM
Secondary Wave Energy	Medium	Medium	Complementary to primary energy
Froude Number (Fr)	Medium	Medium	Indirect effect through hydrodynamics
Drawdown Velocity	Low-Medium	Medium	Better captured by sequence model
Lagged Variables (w lag, T lag, E lag)	Not included	High importance for both outputs	Captures memory and cumulative effects

5.5 Discussion

The findings of this study confirm the role of ship-induced waves in promoting nearshore sediment resuspension within the upper St. Lawrence River, Canada, in agreement with the prior investigations conducted by Haghighi *et al.* (2025) [11]. The relationship between vessel passage and episodic turbidity increases was most pronounced at shallow stations with fine-grained substrates. This pattern is consistent with earlier studies from confined waterways, such as the lower St. Lawrence, Canada, and Savannah Rivers, USA, [46, 135, 136], where repeated vessel activity has been linked to enhanced wave energy, shoreline degradation, and habitat instability.

Hydrodynamic correlations between vessel parameters and wave characteristics support theoretical expectations. Regression analysis indicated that vessel speed, draft, and length exhibited strong positive associations with the primary wave height and associated energy (e.g., $R^2 = 0.78$ for speed versus wave height), in line with prior research on hull geometry and displacement effects [34, 136, 140]. Higher vessel speed led to larger wave heights and more extended wave periods, consistent with Macfarlane’s observations [18]. These relationships remained statistically robust with minimal multicollinearity in the dataset. Such dynamics are particularly relevant in confined river segments, where wave propagation is amplified by bathymetric constraints.

The association between primary wave height and energy displayed a near-quadratic trend ($R^2 = 0.91$), though imperfect due to both the independent treatment of variables in the regression analysis and localized factors, which allowed field-level variability to influence the trend. Variability in bathymetry, sediment texture, and bedform roughness likely contributed to deviations. Additional effects such as wave reflection, interference patterns, and sensor limitations during compound wave events may have influenced the measurements. These findings align with sediment transport theory in dynamic shallow-water systems.

Cargo and tanker vessels produced the highest near-bed shear stress values ($\tau_w > 0.25$ Pa), consistent with expectations given their displacement and draft characteristics [23, 54, 136]. The variation in τ_w between the monitoring stations was mainly attributable to the conditions of the substrate and the depth of the water at each location. Stations N2 and N3, both shallow (< 2.5 m) and composed of finer sediments, recorded the strongest turbidity responses. These results support previous conclusions on the susceptibility to erosion in unconsolidated substrates [23, 46]. Even at sites with coarser sediments, such as N5 and N6, vessel-induced waves generated measurable bed stress [116, 136], demonstrating that wave energy transmission is not limited to soft sediment bed zones.

From a modeling perspective, the application of long short-term memory (LSTM) networks successfully captured delayed turbidity responses following wave events. The persistence of suspended sediment and turbulence—extending beyond the initial wave forcing—suggests cumulative impacts from successive passages. This behavior is in agreement with findings from estuarine and tidal systems, where similar lagged responses have been reported [120]. The LSTM model produced low prediction errors (RMSE = 0.12 NTU; MAE = 0.09 NTU for turbidity), although a slight underestimation during peak events may reflect missing external inputs, including wind forcing, prior sediment loading, or unresolved bedform dynamics. The use of Huber loss improved model robustness by reducing the influence of outliers, supporting stable performance under variable conditions [120, 143].

In terms of management implications, findings highlight the potential benefits of strategies such as vessel speed regulation, hull design optimization, and traffic scheduling [33, 123, 134, 137]. Although reduced speeds generally lower wave amplitudes, this effect may diminish when vessels operate near transcritical or supercritical Froude regimes [37, 141]. High draft to depth ratios can still produce elevated wave energy, underscoring the importance of hydraulic and geometric considerations in regulatory frameworks [84, 136]. Effective implementation of such strategies requires balancing operational efficiency, navigational safety, and environmental resilience.

Taken together, the influence of vessel operating characteristics and site-specific bathymetry reinforces the importance of specifically targeted shoreline protection. Shallow locations with fine sediments exhibited heightened turbidity and shear stress responses, whereas deeper or coarse-grained sites displayed more muted effects. These spatial patterns should inform future sediment monitoring priorities, shoreline management strategies, and the allocation of mitigation efforts.

While the study provides valuable insight into wave-induced sediment dynamics, limitations remain. Although the dataset spans multiple months of high-traffic periods, seasonal and interannual variability were not fully captured, potentially limiting generalizing this study’s findings across broader temporal scales. Furthermore, key environmental drivers such as variability in wind speed, river discharge, and sediment availability were not explicitly included in the model. Future work should incorporate these variables into predictive frameworks and explore longer-term monitoring to assess seasonal and interannual trends. These refinements could improve model accuracy and help distinguish vessel-induced signals from background turbidity fluctuations. Broader application of the methods and models in other riverine settings with varying vessel profiles could also test the transferability and robustness of the approach [34, 143].

5.6 Conclusion

This study adds new information to the findings of Haghighi *et al.* (2025) [11] by quantifying the relationship between vessel operating parameters and nearshore sediment resuspension in the Upper St. Lawrence River. Analysis of wave energy, bed shear stress, and turbidity demonstrated the influence of vessel speed, draft, length, and hull geometry on wave characteristics and their impacts on sediment dynamics.

Higher vessel speeds were associated with increased primary wave energy and corresponding increases in turbidity. Vessels with deeper drafts generated greater near-bed shear stress, particularly in shallow areas with fine sediments. Sequential wave events contributed to cumulative turbidity and shear stress, indicating that residual effects from previous passages influence subsequent wave impacts.

The combined use of time-delayed regression and a bidirectional long short-term memory (LSTM) model provided complementary insights into both static and dynamic relationships between vessel characteristics and sediment resuspension. Although some variability in correlations was attributed to environmental factors and measurement limitations, the predictive performance of the LSTM model demonstrated its effectiveness in forecasting wave-induced sediment disturbance.

These findings support the consideration of vessel speed management, optimized scheduling, and hull design improvements as potential strategies to mitigate wave impacts. Such

measures may contribute to shoreline stability and ecological protection while maintaining commercial navigation efficiency in the Upper St. Lawrence River, Canada.

More broadly, this research demonstrates that ship-induced hydrodynamic forcing plays a critical role in sediment suspension and degradation of nearshore water quality. The findings highlight the importance of considering both vessel characteristics and local geomorphic conditions in planning and management. Future studies should incorporate additional environmental variables such as wind forcing, river discharge, and antecedent sediment supply and extend the temporal scope to capture seasonal and interannual variability. Application of this study framework to other riverine or estuarine systems may offer broader insight into the generalizability of vessel-wave-sediment interactions and inform adaptive mitigation strategies in navigable waterways.

6 Integrated Numerical Modeling of Ship-Generated Wave-Induced Hydrodynamics and Sediment Resuspension in the Upper St. Lawrence River

6.1 Abstract

This study investigates the impact of commercial ship traffic on nearshore hydrodynamics and sediment suspension in the upper St. Lawrence River using an integrated field and numerical modeling framework. High-frequency observations confirmed that ship-generated waves, comprising drawdown and divergent components, trigger short-lived turbidity increases along unprotected cohesive shorelines.

Numerical simulations were performed using the MIKE 21 suite, with ship wave characteristics derived from the USACE Vessel ship-generated wave Prediction Tool (VWPT). Among five submodels tested, the Gates and Herbich formulation was selected based on validation against 14 observed ship passages. Spectral wave simulations, driven by time series inputs scaled to represent approximately 2,500 ship passages per year, reproduced the cumulative effects of both upstream and downstream traffic.

Model outputs revealed energy focusing along concave shoreline segments and localized bed-level gradients, with near-bed velocities remaining below thresholds for sustained sediment transport, confirmed by deposition fraction patterns. While total transport was limited, the episodic nature of wave-induced resuspension poses potential risks to shoreline integrity and water quality. This framework is applicable to other regulated inland waterways where ship-induced wave action influences sediment dynamics.

6.2 Introduction

The increasing use of regulated inland waterways for commercial navigation has intensified concerns about the impacts of ship-generated waves on nearshore hydrodynamics, sediment resuspension, and shoreline stability [46, 59]. These effects are particularly pronounced in confined systems, where vessel-induced disturbances rapidly propagate toward the shoreline, generating drawdown, elevated wave energy, and intensified near-bed turbulence [58, 144]. The upper St. Lawrence River, a water-level-regulated reach of the St. Lawrence Seaway, exemplifies these challenges. Persistent ship traffic, engineered channels, shallow bathymetry, and constrained cross-sectional geometry collectively impose sustained pressure on nearshore habitats and infrastructure [11, 112].

In this study, the term *ship-generated waves* refers to the combined effect of primary (drawdown) and secondary (divergent) wave components generated by transiting vessels [37]. Although wind waves contribute to nearshore dynamics, ship-generated waves are characterized by higher energy flux and greater near-bed orbital velocities, often producing abrupt sediment resuspension events [11, 13]. Drawdown from large, slow-moving ships induces prolonged flow acceleration, while secondary wave trains generate oscillatory shear that sustains particle mobilization [123, 136].

Field measurements in the upper St. Lawrence River have documented sharp, short-lived increases in suspended sediment concentration (SSC) associated with ship passages. Observations from high-frequency wave and turbidity sensors deployed at Jacobs Island and Mariatown during 2022–2023 confirmed the spatial variability of sediment response, with

ship draft, speed, and hull geometry identified as primary contributors to nearshore shear stress [11, 13]. However, the limited duration and spatial coverage of these deployments constrained assessments of cumulative and long-term impacts [23, 120].

To complement field data, Haghighi et al. (2025b) [13] developed statistical models including multivariate regression and long short-term memory (LSTM) networks to predict turbidity responses from ship parameters. While effective for short-term forecasting, these models did not resolve spatial hydrodynamics nor allow evaluation of mitigation strategies.

This study advances earlier work by integrating the Vessel Wake Prediction Tool (VWPT) [145] with DHI’s MIKE 21 Spectral Wave (SW) and Coupled Model FM modules [22, 146] to simulate the propagation of ship-generated waves, near-bed velocities, and short-term sediment transport in the upper St. Lawrence River. Background hydrodynamic conditions were established using the MIKE 21 HD-FM model, incorporating monthly wind data from Ogdensburg International Airport [102].

The modeling framework focuses on ship wave transformation across irregular nearshore morphology, energy delivery to sensitive shorelines, and resulting sediment dynamics. Two monitoring sites, Jacobs Island and Mariatown, were instrumented with 2 Hz RBR Duo3 D.TU depth and turbidity sensors [11, 13], and site-specific turbidity-to-SSC conversion functions were applied to validate model outputs (Section 6.3). Simulations isolated ship-generated wave effects by excluding ambient wind and current forcing.

In line with conventional practice, primary and secondary wave components were modeled independently, and corresponding near-bed shear stresses were evaluated to assess sediment resuspension [21, 123, 135]. The scope of the study is focused on isolating short-term bed-level changes and sediment resuspension driven exclusively by ship-generated wave forcing, without the influence of wind or ambient current conditions. This approach reflects the objective of quantifying the impacts induced by the vessel under regulated flow in a controlled environment.

This study applies a multistage numerical modeling framework to simulate ship wave-induced hydrodynamics and sediment resuspension under typical and reduced-speed conditions. Although long-term morphological trends are outside the scope of this study, prior work in the upper St. Lawrence River has not addressed the localized, spatially distributed impacts of ship-generated waves on cohesive sediment dynamics using a fully coupled, high-resolution approach. This study fills that gap by implementing a large-domain nesting model to establish background hydrodynamic conditions, enabling the integration of the Vessel Wake Prediction Tool (VWPT) with *MIKE 21 SW* and *MIKE 21/3 FM* sediment transport modules. The resulting multistage framework resolves wave transformation, near-bed shear stress, and short-term sediment response at two morphologically distinct shoreline sites. To our knowledge, this is the first application of a physics-based, spatially resolved ship wave-sediment model that fully isolates navigation-induced effects from ambient wind and current forcing in this reach. The findings inform future multi-year simulations, assessments of ship wave-induced cumulative exposure, and the development of evidence-based shoreline protection strategies for regulated fluvial systems.

6.3 Methodology

6.3.1 Study Sites and Input Data Sources

This study builds on previously collected field data from two contrasting nearshore environments in the upper St. Lawrence River: Mariatown and Jacobs Island. These sites were selected based on their differing shoreline morphologies, lack of protective structures, and consistent exposure to commercial ship traffic, as described in Haghighi et al. (2025a) [11]. The modeled reach extends from the Iroquois Dam to Summerstown, Ontario, and is hydraulically regulated by the Iroquois and Moses-Saunders Power Dams, which control water levels for navigation, hydropower generation, and ecological purposes [103]. Mariatown lies within this regulated reach, while Jacobs Island is located downstream of the Moses-Saunders Dam but remains subject to the influence of regulated discharge, which affects water levels and hydrodynamics in the downstream portion of the river.

High-frequency depth and turbidity data were collected using RBR Duo3 D.TU loggers (RBR, Canada) during the 2022 and 2023 navigation seasons. Six loggers were deployed across the two sites, three per site, at depths ranging from 0.5 to 1.5 meters and at distances of 2 to 40 meters from shore. Instruments were mounted approximately 20 cm above the bed, adjusted based on local substrate conditions. Sampling occurred at 2 Hz and covered June to October 2022 and March to October 2023, providing two full open-water seasons of data. Detailed sediment characteristics and loggers deployment locations (sites N1–N6), along with regional bathymetry, are comprehensively described in Haghighi et al. (2025a, Fig. 2, and Table 1) [11]. These datasets were used to extract discrete ship-generated wave events and to validate simulated wave heights and sediment concentration predictions in the present study. A physical erosion rod was installed in June 2022 along the Mariatown shoreline to track potential shoreline displacement during the shipping season. This marker was georeferenced and integrated into ArcGIS-based shoreline change analysis, using both historical aerial imagery and satellite overlays to assess visible erosion. No detectable retreat was observed from the installation point throughout the 2022–2023 navigation period, supporting the interpretation that bed-level changes were primarily subaqueous and wave-induced.

Turbidity data were converted to SSC using a site-specific linear regression model developed based on field measurements from the 2022 and 2023 monitoring campaigns [11]. The linear conversion equation used is defined in Haghighi et al. (2025a) [[11], Eq. (1)], which relates turbidity (NTU) to SSC (g/L) using a site-calibrated slope based on logger N1 data. The resulting SSC values were used to validate model outputs from the DHI MIKE mud transport module. Ship types, dimensions, and operating speeds were obtained from the Automatic Identification System (AIS)-based traffic analysis in Haghighi et al. (2025b) [13]. Two dominant ship types, cargo ships and tankers, were used to construct synthetic wave inputs. Wave parameters were generated using a deterministic ship-generated wave prediction model and compared with logger observations to evaluate model performance. These measured and derived parameters informed the wave forcing conditions applied through VWPT outputs and served as baseline data for validating model performance.



Fig. 42 Study area in the upper St. Lawrence River. Mariatown, Ontario (yellow) lies to the west ($44^{\circ}53'11.22''\text{N}$, $75^{\circ}11'48.44''\text{W}$) and Jacobs Island, Ontario (red) to the east ($45^{\circ}2'47.86''\text{N}$, $74^{\circ}33'32.05''\text{W}$). Hydraulic control structures include Iroquois Dam (green) and Moses-Saunders Power Dam (blue). (Source: Google Earth, 2025)

6.3.2 Numerical Model Framework Overview

This study used a staged modeling framework to simulate river hydrodynamics, ship-generated wave propagation, and its impact on sediment dynamics in two near-shore environments in the upper St. Lawrence River. A combination of specialized numerical tools was selected to reflect the distinct spatial scales and physical dynamics associated with each process. The primary modeling components included the DHI MIKE 21 software suite, including the Flow Model FM (HD), Spectral Wave (SW), and Coupled Model FM modules, as well as the Vessel Wake Prediction Tool (VWPT), developed by the U.S. Army Corps of Engineers, to estimate ship-induced wave characteristics.

The use of separate but integrated models was necessary due to the hydraulic structure of the river system and the modeling objectives. The study area lies within the river reach between Iroquois and Summerstown, Ontario, which includes a hydraulically regulated section bounded by the Iroquois and Moses-Saunders dams. Therefore, a coarse-resolution hydrodynamic model was developed using MIKE 21 HD-FM to represent baseline flow conditions over this 65-kilometer domain, with the Moses-Saunders Dam included as a gate structure within the model domain. Average monthly wind data from the Ogdensburg International Airport station, provided by the U.S. National Weather Service [102], were included only in the large-domain nesting model to support the development of background water level gradients.

This large-domain model provided spatially and temporally varying boundary conditions, including water levels and depth-averaged velocity fields, for two nested, high-resolution models centered around Mariatown and Jacobs Island. The extracted water level series were compressed to align with the synthetic one-year ship traffic time series, and distributed along segmented open boundaries. These boundary inputs informed the small-domain SW and FM simulations but did not include additional wind or ambient current forcing.

To simulate wave forcing conditions, the VWPT was used to generate estimates of ship-generated wave heights and peak periods at the centerline of the navigation channel. These predictions were derived using detailed ship parameters and validated against high-frequency logger data, as reported in previous field studies. A synthetic time series representing one year of ship activity was constructed based on these validated outputs. For each study site, this wave series was introduced along a segmented boundary within the MIKE 21 SW model domain, where each boundary node received a time-shifted input based on its distance from a virtual ship path and an average ship transit speed. This enabled dynamic simulation of wave propagation from the navigation channel into the nearshore zone.

Following SW simulations, the resulting wave fields, including significant wave height, peak period, wave direction, and near-bed orbital velocity, were reintroduced into the high-resolution domains of each site. These domains, refined near the shoreline, were used to run the MIKE 21/3 Coupled Model FM with the cohesive sediment transport module. To isolate the effects of ship-generated waves, no high-resolution wind or ambient current forcing was applied in the SW or 21/3 FM models. This configuration was supported by the nesting model, which confirmed minimal nearshore background currents. The setup enabled a one-year simulation of ship-induced hydrodynamic and sediment transport responses, including near-bed velocities, SSC, and bed level change, capturing both sediment resuspension and localized redeposition patterns under wave forcing.

A schematic representation of the modeling workflow used in this study, showing sequential steps for mesh generation, hydrodynamic nesting with wind forcing, boundary condition extraction, VWPT-based wave input generation, wave propagation, and coupled wave-sediment transport modeling is presented in Figure 43. The framework integrates validation at multiple stages and supports sediment response comparison under representative and reduced-speed scenarios at two nearshore sites.

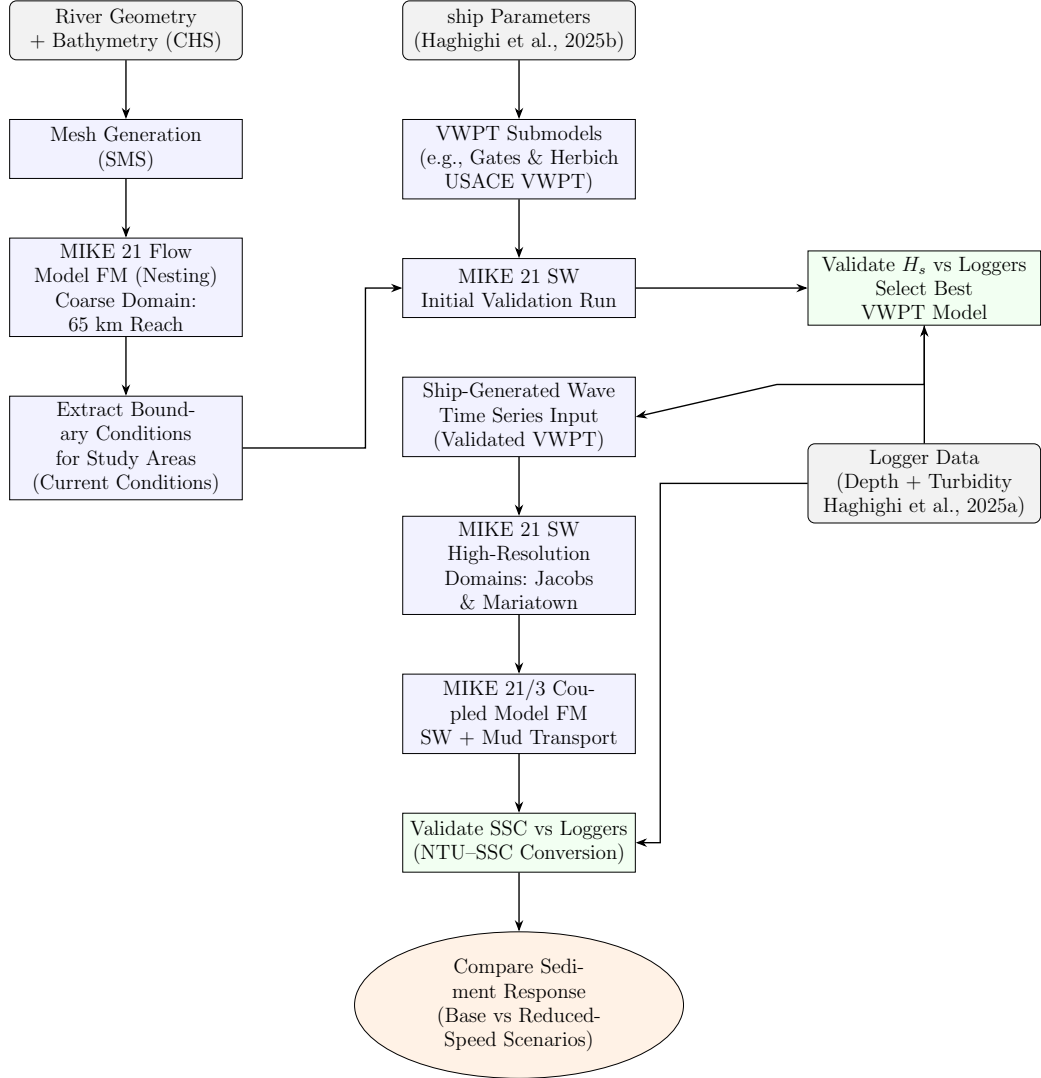


Fig. 43 Modeling workflow used in this study, showing sequential steps at two nearshore study areas.

6.3.3 Model Mesh and Boundary Conditions

The modeling framework employed a multilayered, flexible mesh strategy to represent hydrodynamic and wave processes across multiple spatial scales. Three distinct MIKE 21 model domains were developed: (1) a coarse-resolution hydrodynamic model (HD-FM) for the 65 km river reach from Iroquois Dam to Summerstown, and (2) two nested high-resolution domains at Mariatown and Jacobs Island, used for wave (SW) and coupled hydrodynamic-sediment transport (FM) simulations. Mesh development and resolution details are summarized in Table 16. Meshes were developed using Surface Water Modeling Software

(SMS) v13.3, community edition, with resolution varying from 0.1 m nearshore to 10 m offshore. A sensitivity test confirmed negligible differences in wave height and SSC outputs beyond this configuration, avoiding sub-meter overhead without compromising numerical stability (Table 16).

Table 16 Model domain configurations, including spatial extent, mesh resolution, and boundary condition sources for each model component.

Domain	Model Type	Mesh Resolution	Boundary Conditions
Iroquois to Summerstown	MIKE 21 HD-FM (nesting model)	100 m (main channel), 20–30 m (near Mariatown and Jacobs)	Inflow (Iroquois), outflow (Summerstown), dam regulation, wind forcing
Jacobs Island	MIKE 21 SW / FM	0.1–1 m (shoreline), 5–30 m (offshore)	Time-varying water level and flow input from HD-FM; wave boundary from VWPT-based synthetic series
Mariatown	MIKE 21 SW / FM	0.1–1 m (shoreline), 5–30 m (offshore)	Time-varying water level and flow input from HD-FM; wave boundary from VWPT-based synthetic series

The coarse-resolution nesting model simulated baseline flow conditions and generated boundary inputs for the high-resolution wave and sediment transport domains. Mesh resolution was approximately 100 m in the main channel and refined to 20–30 m near Jacobs Island and Mariatown. Bathymetry was sourced from the Canadian Hydrographic Service’s NONNA dataset and referenced to CGVD2013 [147]. A constant Manning number of $32 \text{ m}^{1/3}/\text{s}$ (equivalent to Manning’s $n \approx 0.031$) was applied uniformly across the domain. This value lies within the reported range of $28\text{--}38 \text{ m}^{1/3}/\text{s}$ (or $n \approx 0.026\text{--}0.035$) commonly used for large, regulated river channels with cohesive beds and moderate vegetation density [148]. The selected value was verified through model calibration against observed water level and discharge data.

Boundary forcing included inflow at Iroquois Dam, regulated outflow at Moses–Saunders Dam, and average monthly wind data from Ogdensburg Airport [102, 103]. The Moses–Saunders Dam was modeled as a gated structure, dynamically operated based on the upstream–downstream water level gradient. Gate thresholds were calibrated to match observed discharge records from the International Lake Ontario–St. Lawrence River Board [103]. The nesting model produced dynamic water level time series and depth-averaged velocity fields, which were exported and interpolated along open boundaries of the high-resolution models.

Model outputs were validated against observed water levels at Morrisburg-14660 station [149], and further corroborated by nearshore Acoustic Doppler Current Profiler (ADCP) measurements collected during 2021 fieldwork. The ADCP unit was mounted on a small boat and used to sample nearshore transects at both sites. These measurements confirmed

that nearshore current speeds were negligible and remained between 0 and 1 m/s. The final mesh structure is shown in Figure 44.

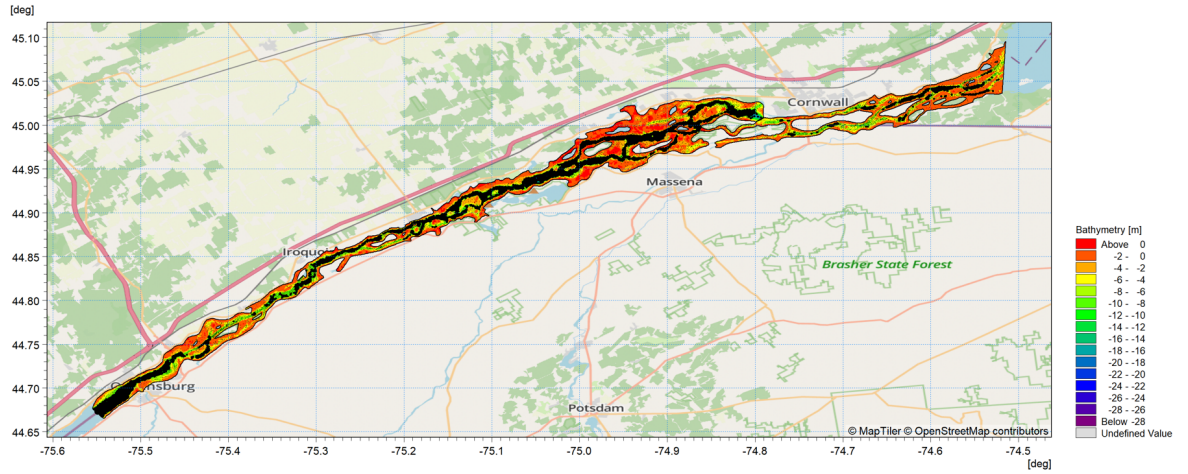


Fig. 44 MIKE 21 HD-FM bathymetry and mesh coverage for the Iroquois to Summerstown nesting model.

The high-resolution domains were created using the SMS interface, with graded mesh refinement from 0.1–1 m near logger sites and shorelines, transitioning to 5–30 m offshore. These meshes supported the simulation of nearshore wave transformation, sediment resuspension, and local deposition. Each domain received dynamic boundary inputs of water level and velocity from the nesting model, compressed to match the synthetic one-year wave input time window.

Wave boundaries in the SW model were forced using synthetic time series derived from VWPT outputs, applied to a segmented boundary line near the navigation channel. Node-specific timesteps were assigned based on relative ship passage average speed to move from one node to another, considering their equal distance along the middle of the shipping lane. No wind or ambient current forcing was included in the SW or FM models, allowing isolation of ship-generated wave-induced sediment dynamics.

Figure 45 presents the mesh design for Jacobs Island, while Figure 46 shows the gradational structure for Mariatown.

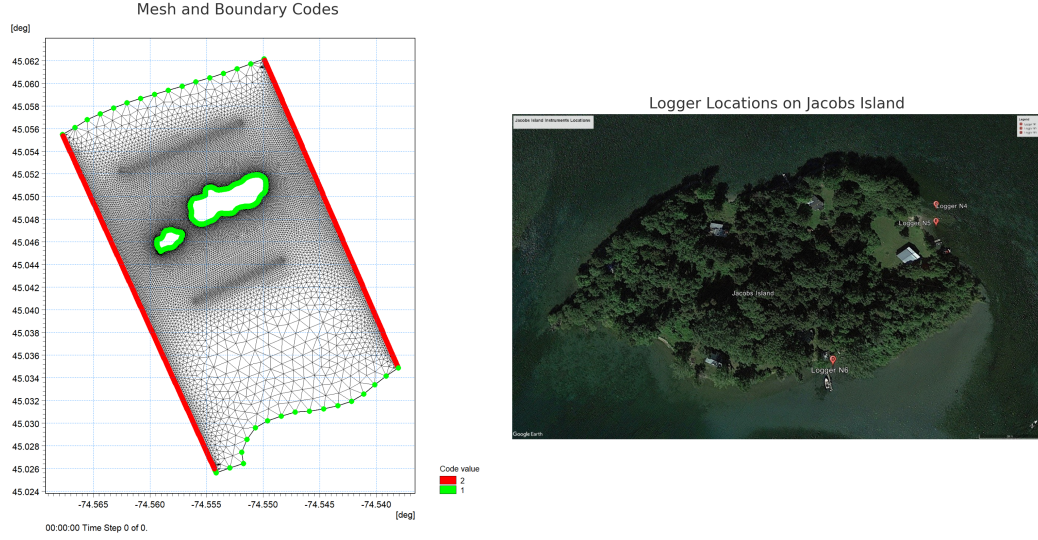


Fig. 45 Multi-layered high-resolution mesh configuration for the Jacobs Island domain, showing detailed shoreline refinement. Code values: 1 = closed boundary (green), 2 = open boundary (red). Boundary conditions were defined separately in the model setup.

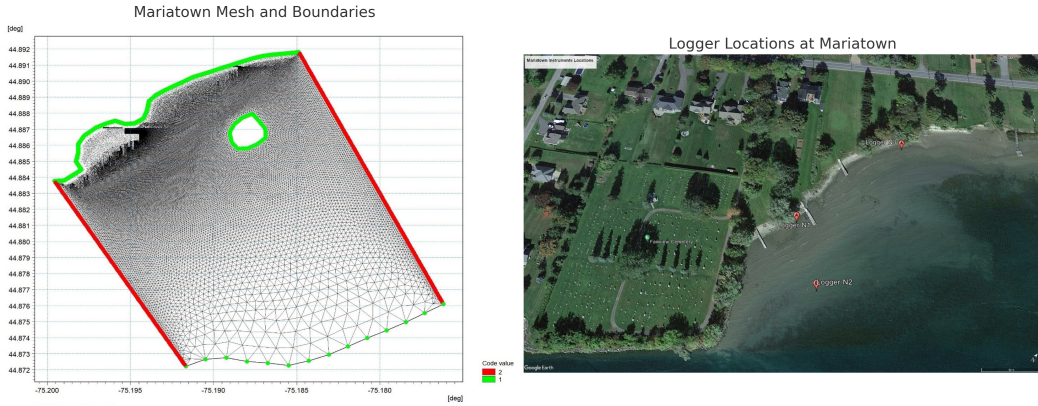


Fig. 46 Multi-layered high-resolution mesh configuration for the Mariatown domain, highlighting mesh gradation from shoreline to deeper waters. Code values: 1 = closed boundary (green), 2 = open boundary (red). Boundary conditions were defined separately in the model setup.

Mesh generation in SMS allowed greater flexibility than native MIKE editors and supported structured refinement near shorelines and logger transects [24]. Prior studies have shown diminishing accuracy returns for ultra-fine mesh sizes in stable riverine environments

and that sub-meter elements can hinder model stability without improving predictive skill [150, 151].

Mesh sensitivity analysis confirmed that spatial resolution below 1 m did not significantly improve model performance for wave height, near-bed velocity, or SSC predictions. Finer resolution also increased computational time and reduced timestep thresholds. Final mesh configurations were selected to optimize trade-offs among stability, accuracy, and runtime efficiency while maintaining agreement with logger observations.

6.3.4 Wave Simulation

Wave forcing parameters for simulation were derived using the U.S. Army Corps of Engineers' VWPT. Five VWPT submodels were evaluated for their predictive performance against 14 observed ship passages with recorded wave height, drawdown, and near-bed velocity near the shipping lane and at logger sites.

Each passage was simulated using all submodels and the resulting time series were compared to the measured wave data. The Gates and Herbich submodel consistently produced the lowest root-mean-square errors (RMSE), with deviations below 10% for primary wave height at nearshore sensors. Accordingly, this submodel was selected for all subsequent simulations.

Table 17 Comparison of VWPT sub-models tested for multiple track alignments.

Model	Type	Inputs	Outputs
Gates and Herbich	Semi-Empirical	Length, Speed, Depth, C_b , Geometry	Drawdown, Wave Height
PIANC	Semi-Empirical	Length, Displacement, Depth	Drawdown
Sorensen	Semi-Empirical	Length, Speed, Depth	Bed Shear, Velocity
Blaauw et al.	Numerical	Hull, Propeller, Thrust	ship generated wave Pressure Field
Kriebel and Seelig	Empirical	Length, Speed	Energy Attenuation

Following model selection, representative ship operating conditions were used to define both observed and reduced-speed scenarios. For each scenario, VWPT was used to generate wave parameters, including significant wave height (H_s), and near-bed orbital velocity. These were used as boundary inputs in subsequent wave propagation simulations. Gates and Herbich (1977) Submodel Formulation

The selected VWPT submodel corresponds to the Gates and Herbich formulation documented as Model 4 in the U.S. Army Corps of Engineers report by Sorensen [152]. This model predicts near-field bow wave height and the far-field divergent wake pattern using empirical relationships derived from controlled large-vessel experiments.

The bow (near-field) wave height is expressed as:

$$H_b = K_w \frac{B}{L_e} \frac{V^2}{2g}, \quad (30)$$

where B is the vessel beam, V the vessel speed, g gravitational acceleration, and K_w an empirical coefficient obtained from regression curves as a function of $V/\sqrt{L_v}$, with L_v the vessel length.

The effective entrance length L_e is estimated from experimental data as:

$$\frac{L_e}{L_v} = 0.417 - 0.00235 L_v. \quad (31)$$

The spacing of cusp points for the divergent wave system in deep water is given by:

$$x = 1.21 \frac{V^2}{g} (2N + 1.5), \quad N = 1, 2, 3, \dots \quad (32)$$

The corresponding maximum cusp-point wave height decays with increasing N as:

$$H_m = H_b (2N + 1.5)^{-0.33}. \quad (33)$$

In VWPT, these expressions are used together with hull coefficients (B , L_v , T , C_b) to generate primary drawdown and divergent wave heights for boundary forcing. This submodel produced the lowest RMSE across 14 observed ship passages and was therefore selected for all simulations.

Table 18 ship scenarios used in wave simulations.

ship Type	Length (m)	Speed (m/s)	Scenario
Cargo	200	5.45	Base Case
Cargo	200	4.00	Mitigation 1
Tanker	225	5.00	Base Case
Tanker	225	4.00	Mitigation 2

6.3.5 Wave Time Series and Sediment Modeling

To simulate the cumulative effects of commercial vessel traffic, a synthetic wave time series was constructed based on 100 repeated, continuous ship passages for each of the 14 representative ships, as detailed in the Results section. The wave parameters derived from these passages were averaged and expanded into a one-year continuous sequence representing 2,500 ship passages. This extended series incorporated alternating upstream and downstream wave directions. The wave height time series was applied as dynamic input to the MIKE 21 SW model using the full spectral formulation.

Table 19 MIKE 21 SW Model Configuration

Mesh Resolution	10 m (offshore), 1 m–0.1 m (nearshore)
Spectral Discretization	25 frequencies $\times$ 12 directions
Time Step	24 s
Forcing Input	VWPT outputs (validated with logger data)
Wave Spectrum	Full spectral formulation, no spreading
Wave Direction	Bidirectional (upstream/downstream)
Annualized Representation	Synthetic series for $\sim$ 2,500 passages/year
Boundary Forcing	30–32 dynamic nodes per site (5 wave parameters)

Dynamic wave input files in `.dfs1` format were prepared for both sites, consisting of approximately 250,000 time steps. Ship passages were sequenced continuously, with each new event initiated at the upstream boundary node only after the wave energy from the previous passage had fully decayed to zero, thereby preventing any overlap or interaction between successive wave trains. Five parameters were specified per node at each time step: wave height (m), peak period (s), mean wave direction ($^{\circ}$), directional spreading index (n), and wave volume (m^3). Boundary nodes were distributed along the middle of the shipping lane, 30 at Jacobs Island and 32 at Mariatown, to simulate directional wave propagation. Corresponding water level time series, exported from the nesting HD model, were proportionally compressed to align with the synthetic wave time series, maintaining temporal consistency across all inputs.

To isolate wave-specific sediment responses, wind and ambient current forcing were excluded from both the MIKE 21 SW and 21/3 FM simulations. Wind was only included in the large-domain HD model to support the development of water level gradients. This modeling design ensured that sediment transport outputs reflected the response to ship wave forcing alone, uncontaminated by meteorological variability.

MIKE 21 SW outputs of wave radiation stress were passed into MIKE 21/3 FM, which used the cohesive sediment module to simulate suspended sediment concentration and bed level thickness change. Combined wave–current shear stress was calculated from synthetic wave forcing and compressed water level gradients (HD output), thus, the computed shear stress includes both the wave and nesting model exported current components. A modified Partheniades entrainment function governed sediment resuspension, based on site-specific critical shear stress thresholds.

The simulations incorporated historical cohesive sediment characteristics from the Cornwall region [8], using a unified grain size (D_{50}) of 0.05 mm across the domains, consistent with the field-measured response to turbidity reported by Haghighi et al. (2025a, 2025b) [11, 13].

Table 20 MIKE 21/3 FM Sediment Transport and Coupled Model Parameters

Sediment Type	Mixed cohesive (Cornwall region)
Grain Size (D_{50})	20–150 μm (average 0.05 mm)
Critical Shear Stress (τ_c)	0.05–0.1 N/m^2
Settling Velocity	0.001–0.003 m/s
Turbidity–SSC Conversion	Calibrated linear
Bottom Roughness (Manning’s n)	0.020 (open), 0.035 (nearshore)
Eddy Viscosity	0.28 m^2/s
Wave Breaking Coefficient (γ)	0.73
SW Bottom Friction Coefficient	0.038

6.4 Results

This study integrates empirical and process-based modeling to simulate ship-generated wave-induced hydrodynamics and sediment responses in the upper St. Lawrence River. Results are grouped into four components: (1) background hydrodynamic conditions, (2) wave prediction

and validation, (3) ship-generated wave propagation and shoreline energy delivery, and (4) near-bed sediment resuspension.

Model outputs were generated for both representative and mitigation scenarios. However, to maintain clarity and avoid repetition, this section presents only the results from the representative operating speed scenario. These results represent typical ship classes and transit speeds observed during the monitoring period. All simulations, including those under reduced-speed conditions, were completed and are discussed later in the manuscript.

This modeling framework was designed to align with the specific hydraulic and morphological characteristics of the upper St. Lawrence River. By integrating the empirical VWPT with DHI's MIKE 21 HD/SW/FM modules, the approach combines ship-specific wave prediction with spatially distributed hydrodynamic and sediment transport simulations. The modular structure allowed for iterative testing and refinement at two geomorphologically distinct sites—Jacobs Island and Mariatown—each exhibiting different shoreline configurations, bathymetric slopes, and exposure to ship traffic. This setup provided a method to quantify ship-generated wave impacts under real-world navigation patterns.

6.4.1 Hydrodynamic Background Conditions

The MIKE 21 HD-FM model was used to simulate baseline flow conditions across a 65 km domain. Current distribution under maximum discharge at the upstream Iroquois Dam ($9,040 \text{ m}^3/\text{s}$) are shown in Figure 47.

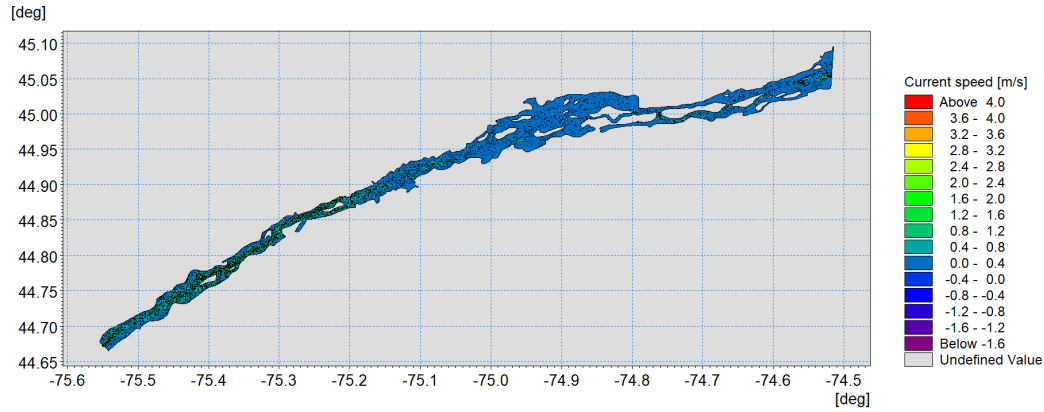


Fig. 47 Current distribution under maximum discharge conditions ($9,040 \text{ m}^3/\text{s}$) at the upstream Iroquois Dam.

In the Jacobs Island nested domain, channelized zones exhibited elevated flow velocities, while lateral shelves experienced reduced velocities. Flow direction vectors revealed circulation patterns influenced by nearshore bathymetry, including directional convergence near constricted channels. Drag coefficient distributions (Figure 49) indicate higher bed resistance in shallow and vegetated zones.

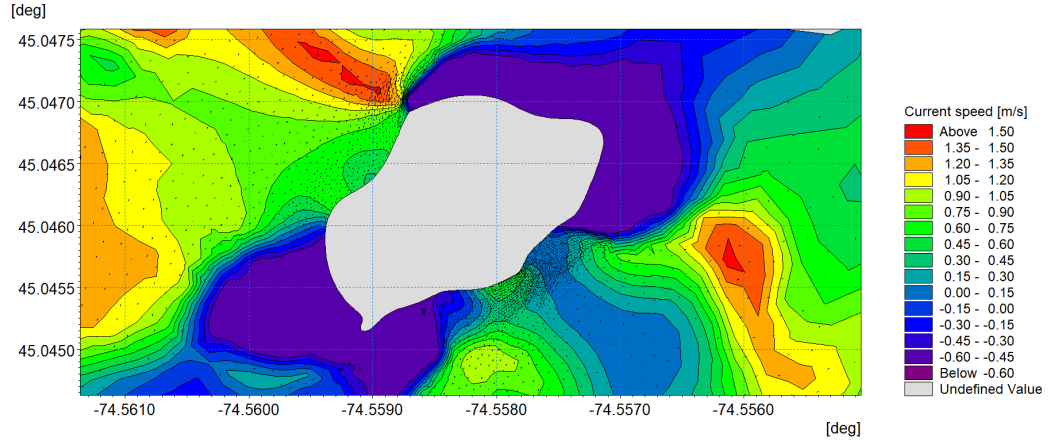


Fig. 48 Current distribution in the Jacobs Island domain derived from the nesting model.

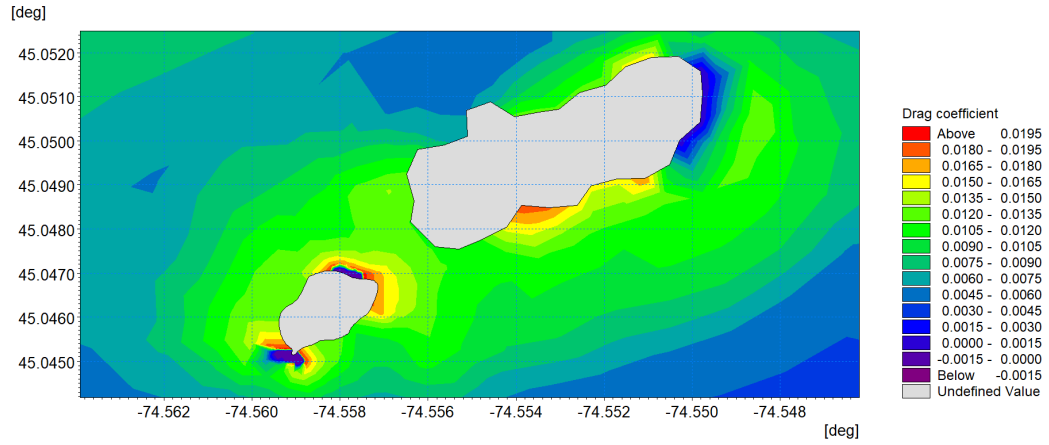


Fig. 49 Drag coefficient distribution in the Jacobs Island domain derived from the nesting model.

At Mariatown, flow velocities peaked near mid-channel features, and localized recirculation occurred along concave shoreline features (Figure 50). Flow direction vectors aligned with the channel axis, while drag distributions showed bottom roughness variability (Figure 51).

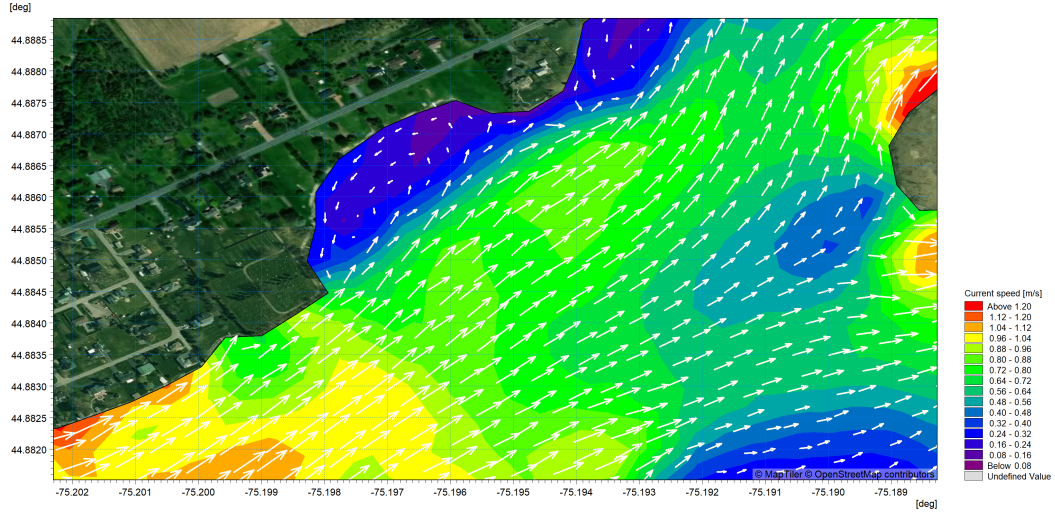


Fig. 50 Current distribution in the Mariatown domain derived from the nesting hydrodynamic model. Near-shore velocities remained below 0.3 m/s, aligning with ADCP measurements.

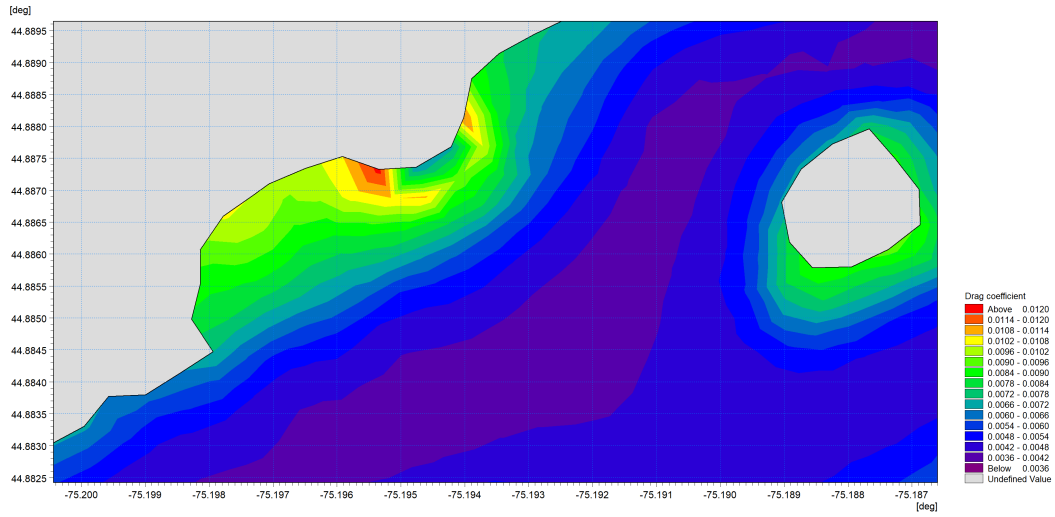


Fig. 51 Drag coefficient distribution in the Mariatown domain derived from the nesting model.

6.4.2 Wave Prediction and Validation

Wave height predictions were generated using the Gates and Herbich formulation in VWPT, which provided consistent estimates among the tested submodels (Figure 52). The resulting

substantial wave heights (SWH) were validated at logger sites N1 and N3 using MIKE 21 SW.

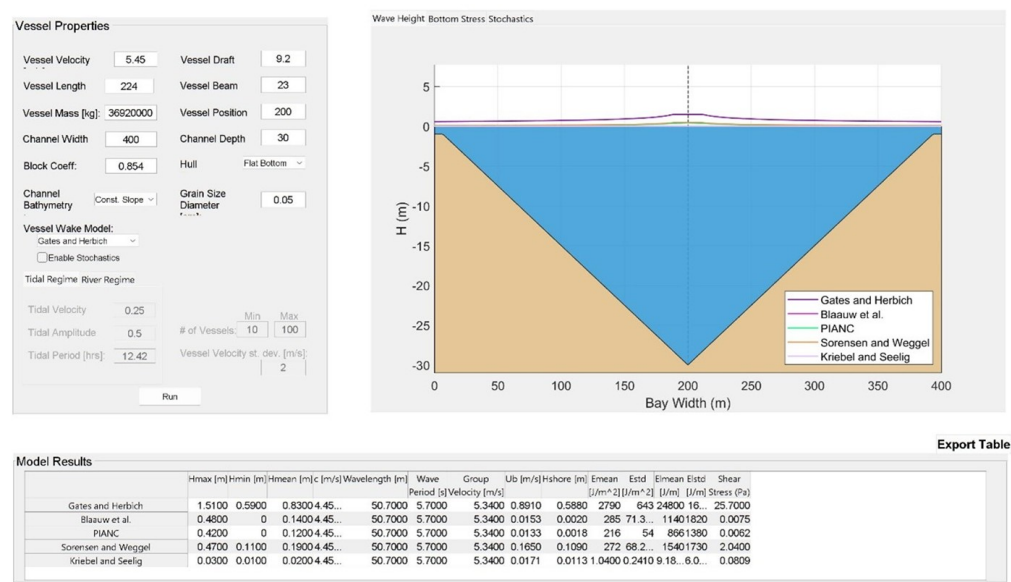


Table 21 Validation of VWPT submodel (Gates and Herbich) for 14 observed ship passages. Errors are calculated for maximum wave height ($H_{\max}$) using logger data.

Passage ID	Observed $H_{\max}$ (m)	Modeled $H_{\max}$ (m)	Error (%)
1	0.210	0.226	7.6
2	0.180	0.175	2.8
3	0.200	0.210	5.0
4	0.195	0.183	6.2
5	0.215	0.222	3.3
6	0.240	0.230	4.2
7	0.225	0.212	5.8
8	0.218	0.207	5.0
9	0.205	0.198	3.4
10	0.190	0.183	3.7
11	0.235	0.246	4.7
12	0.198	0.210	6.1
13	0.222	0.211	5.0
14	0.205	0.195	4.9

6.4.3 Wave Propagation and Energy Distribution

Wave propagation was simulated using the MIKE 21 SW model, and VWPT-derived wave time series representing approximately one year (2500) of ship passages, as described in Section 6.3.5. The resulting spatial distributions for Mariatown are shown in Figures 53 and 54, illustrating significant wave height and wave power, respectively.

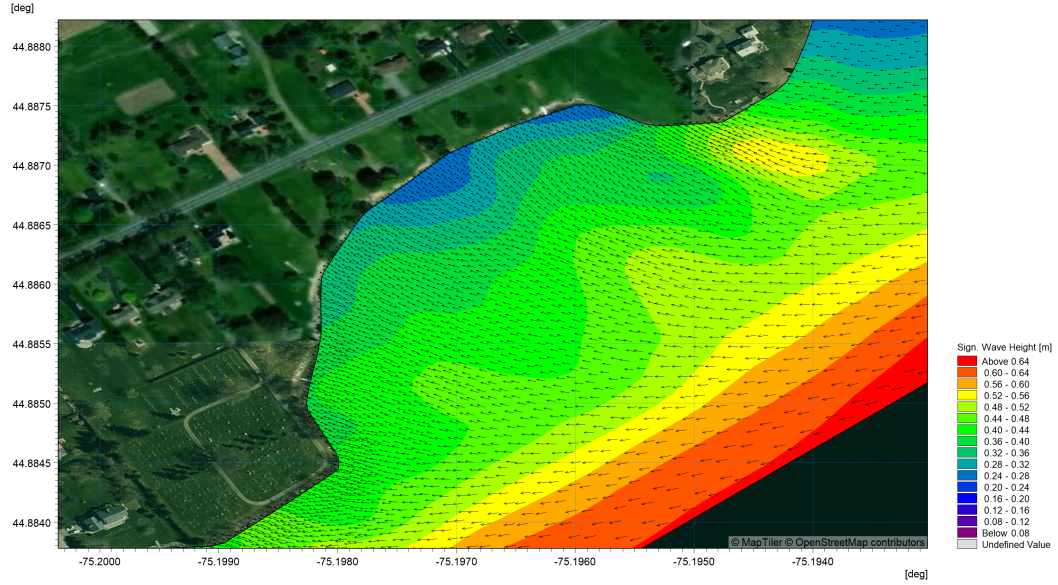


Fig. 53 Simulated significant wave height distribution near Mariatown, integrated over one year of synthetic ship traffic (2,500 passages). Vectors indicate wave direction.

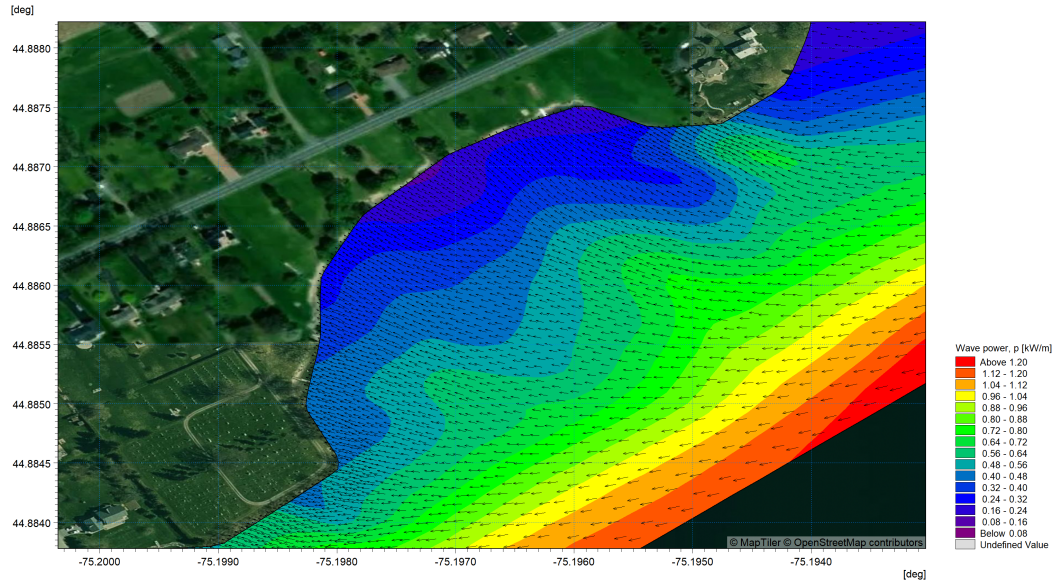


Fig. 54 Simulated wave power distribution (kW/m) near Mariatown, integrated over one year of synthetic ship traffic (2,500 passages). Vectors indicate wave direction.

Wave propagation outputs for Jacobs Island are shown in Figures 55 and 56, representing simulated significant wave height and wave power distributions, respectively.

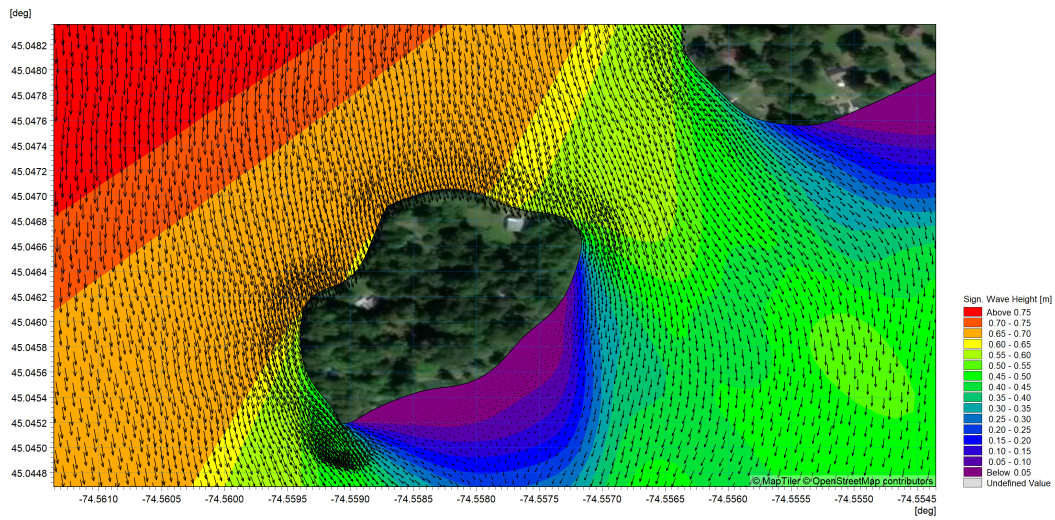


Fig. 55 Simulated significant wave height distribution near Jacobs Island, integrated over one year of synthetic ship traffic (2,500 passages). Vectors indicate wave direction.

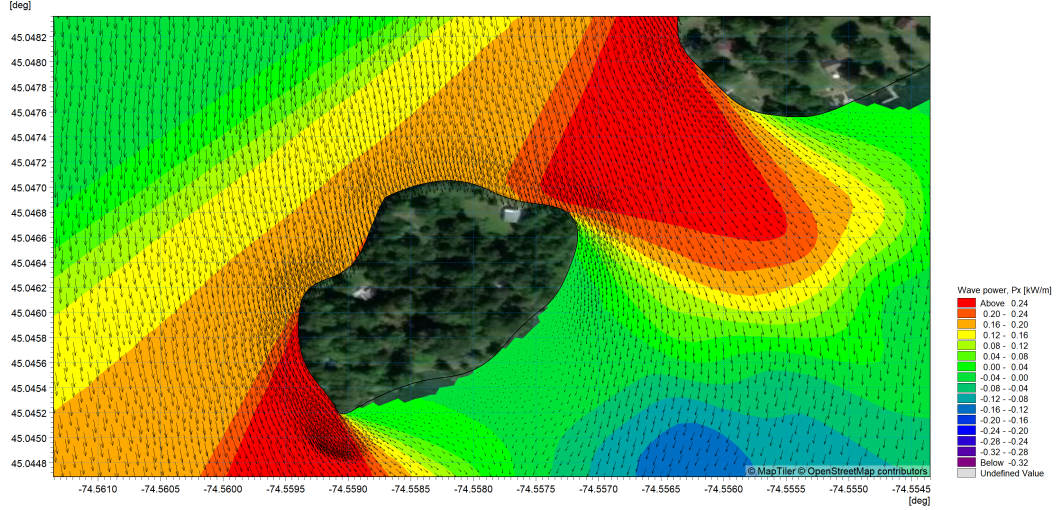


Fig. 56 Simulated wave power distribution (kW/m) near Jacobs Island, integrated over one year of synthetic ship traffic (2,500 passages). Vectors indicate wave direction.

6.4.4 Near-Bed Dynamics and Sediment Response

This subsection presents MIKE 21/3 FM simulation outputs for horizontal near-bed velocity, cumulative bed thickness change, and total suspended sediment concentration (TSSC, hereafter referred to as SSC) at the Mariatown and Jacobs Island domains. The results illustrate spatially resolved sediment behavior driven exclusively by ship-generated wave forcing, with ambient currents and wind explicitly excluded. As will be shown, sediment was primarily resuspended by wave-induced near-bed shear and subsequently redeposited in the nearshore zone, with no evidence of net bed erosion.

Model outputs included horizontal near-bed velocities (Figure 57) and bed thickness change (Figures 58, 59, 60, 61). Wave focusing along nearshore shelves intensified bottom shear stress, but horizontal velocities remained low, with maximum values below 0.0007 m/s, insufficient to initiate transport. The observed resuspension was instead driven by wave-induced orbital motion. Total bed thickness changes remained minimal, with maximum deposition values below 0.00012 m. The “Deposition – fraction 1” output (Figure 59) shows time-averaged deposition flux ($\text{kg}/\text{m}^2/\text{s}$), with a maximum of 4.4×10^{-6} . In contrast, “Total bed thickness change” (Figure 58) represents net elevation change (m) over the full simulation. Both are cumulative but reflect different aspects of the bed response.

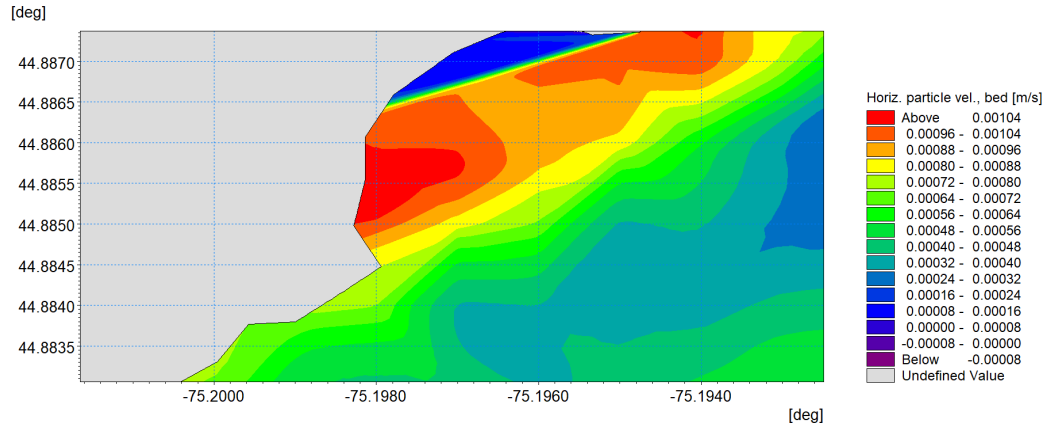


Fig. 57 Simulated horizontal particle velocity near bed layer at Mariatown (MIKE 21/3 FM).

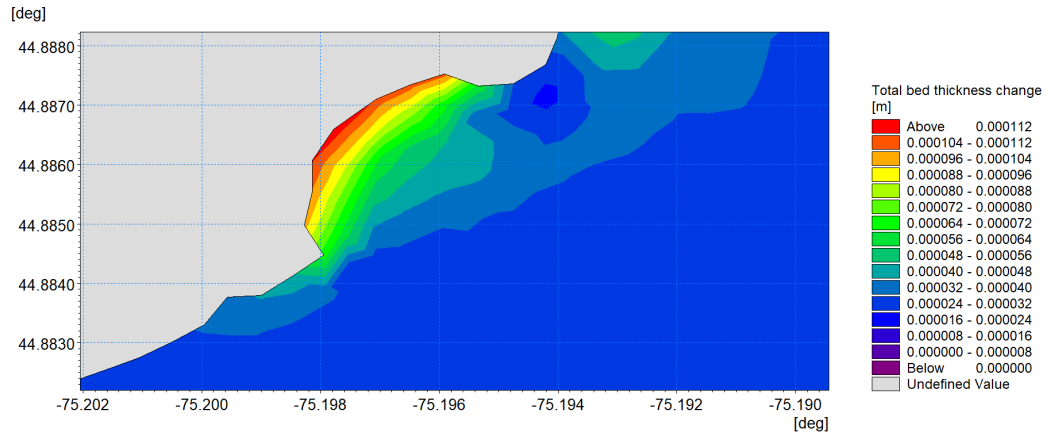


Fig. 58 Simulated total bed thickness change in Mariatown domain (MIKE 21/3 FM, mud transport module).

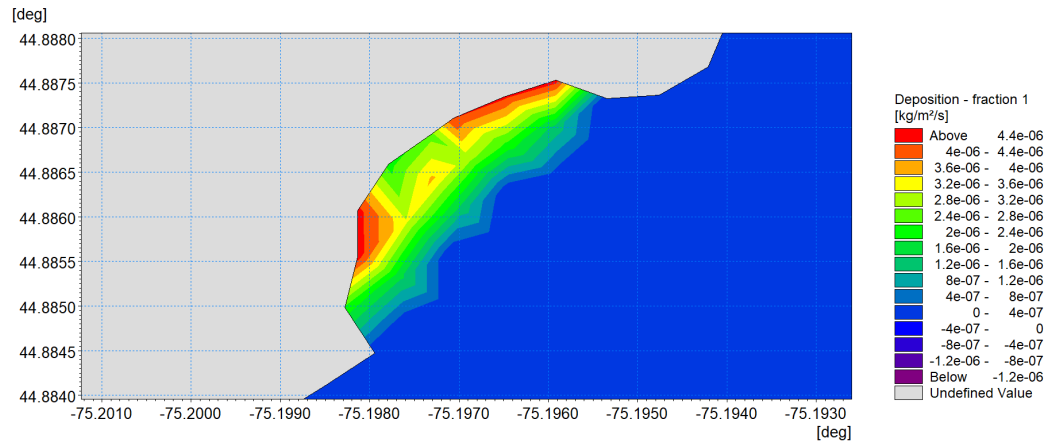


Fig. 59 Zoomed view of nearshore bed response in Mariatown domain showing localized deposition patterns (MIKE 21/3 FM, mud transport module).

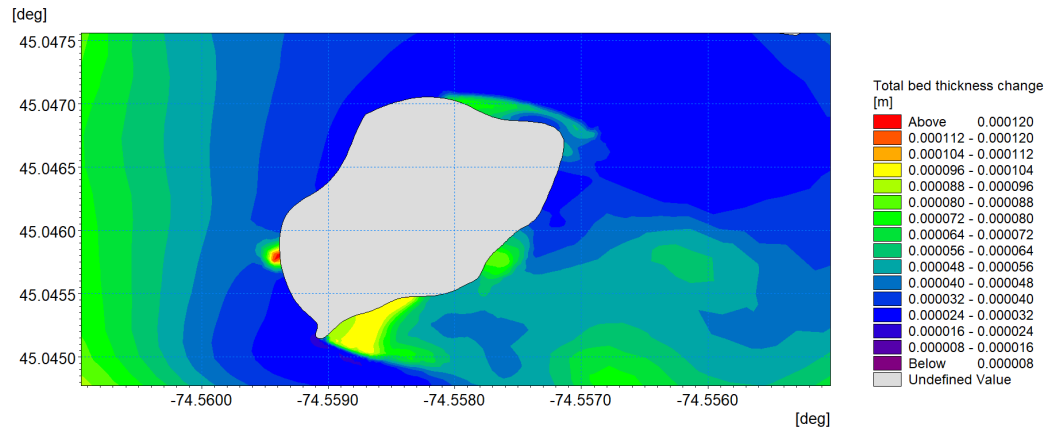


Fig. 60 Simulated total bed thickness change in Jacobs Island domain.

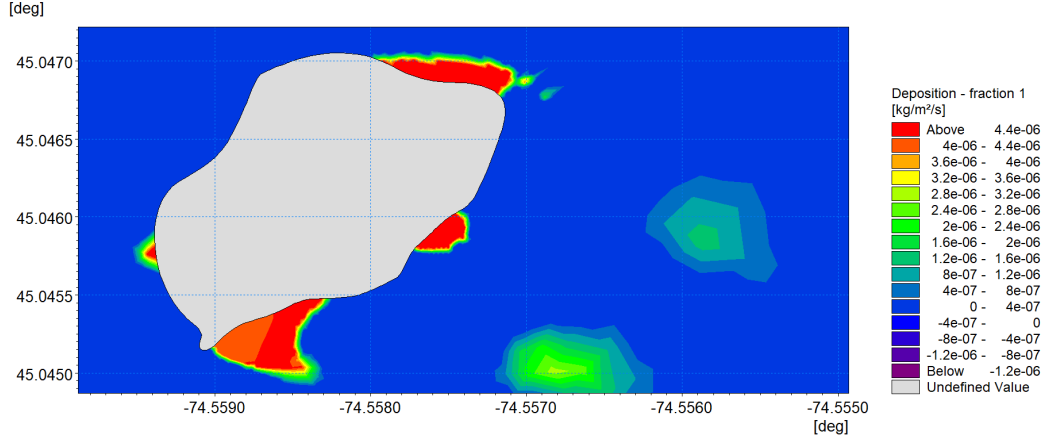


Fig. 61 Zoomed view of nearshore bed response near Jacobs Island showing sediment redeposition.

Simulated TSSC values represent the residual concentration at the final time step of ship passages (2,400 seconds after the passage). Values were extracted at grid cells corresponding to logger locations and averaged approximately 0.0049 kg/m^3 across both sites.

Although logger-derived average SSC values were higher than the simulated residuals, the modeled deposition flux of $4.4 \times 10^{-6} \text{ kg/m}^2/\text{s}$ indicates that up to 10 g/m^3 of suspended sediment had settled 2,400 seconds after a single ship passage. This is consistent with Haghighi et al. (2025a) [11], who observed that turbidity typically returns to near pre-passage levels within 40 minutes. The simulation reproduces this temporal decay but simplifies substrate conditions through the application of a uniform cohesive D_{50} , which may lead to local discrepancies, particularly at rocky sites like N4. While field measurements showed lower SSC at N4 compared to N5, the simulation produced higher values at N4 due to its full exposure to incident wave energy, whereas N5 is partially shielded by a jetty between the two stations, as shown in Figure 45.

Despite these limitations, several spatial patterns are consistent with field observations. Simulated SSC at N1 and N3, both nearshore and shallow, was slightly higher than at offshore N2 (1.5 m depth), aligning with expected shoreline-driven resuspension gradients. Logger placements and shoreline proximity are shown in Figures 45 and 46. Additionally, the relative SSC levels between N5 and N6 were correctly represented: both field and model data show N6 with the highest concentrations in the Jacobs domain, reflecting its location along a more current-exposed shoreline.

These results reflect post-passage, 2,400 seconds (40 minutes) after the initial passage detection, suspended loads rather than peak turbidity during active wave forcing. Throughout the full one-year simulation, both the magnitude and spatial distribution of SSC remained consistent, indicating that resuspended sediments largely settled before the initiation of each new ship passage. Figures 62 and 63 present representative SSC fields for the Mariatown and Jacobs Island domains, respectively.

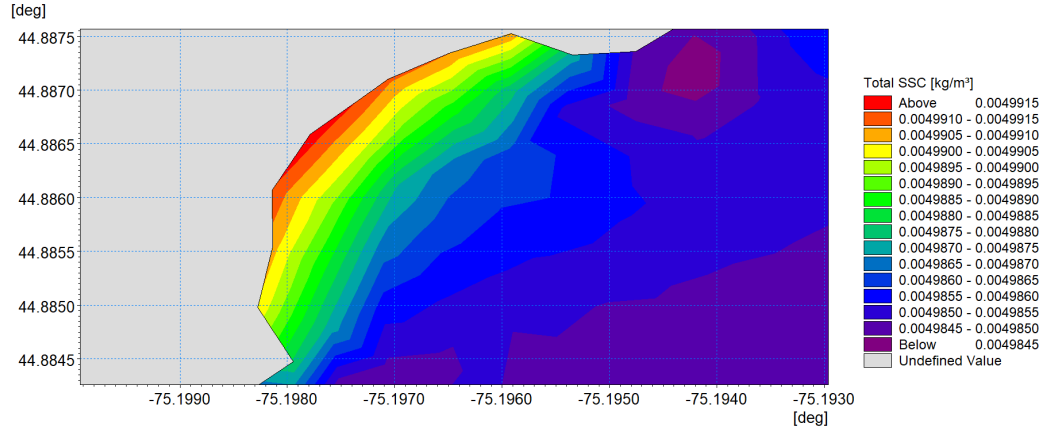


Fig. 62 Zoomed view of elevated SSC in nearshore regions of Mariatown domain.

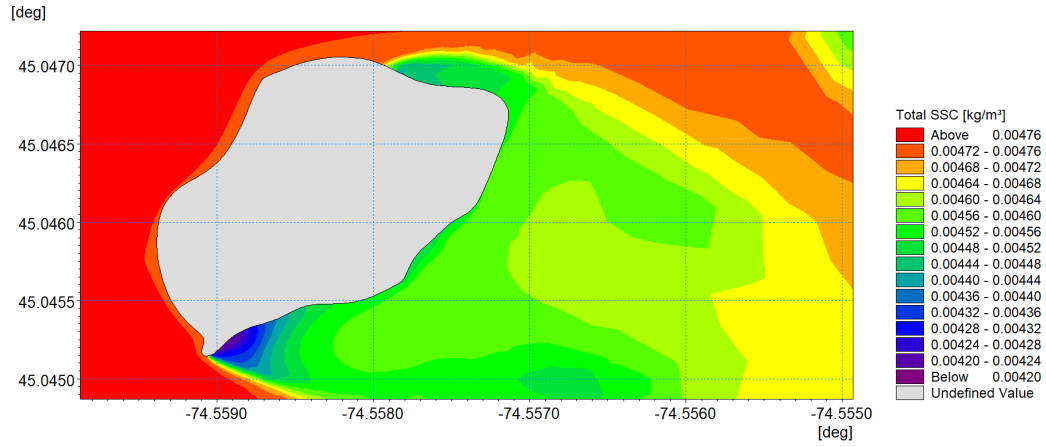


Fig. 63 Zoomed view of elevated SSC in nearshore regions of Jacobs Island.

The effectiveness of reduced-speed scenarios in mitigating sediment resuspension was evaluated using key hydrodynamic and wave metrics across both sites. Table 22 summarizes the relative reduction in near-bed velocity, wave height, and wave power under a 30–35% vessel speed reduction, consistent with mitigation recommendations from local navigation authorities.

Under the assumption of cohesive sediment substrate conditions across the domains (D50) and absence of ambient transport forces, the simulation results suggest only moderate sensitivity of nearshore sediment response to vessel speed reduction. Although wave energy and near-bed velocities declined under the reduced-speed scenario (4.00 m/s compared to

Table 22 Comparison of model outputs under representative (Rep.) and reduced-speed (Red.) scenarios for both sites.

Metric	Jacobs Island			Mariatown		
	Rep.	Red.	Reduction (%)	Rep.	Red.	Reduction (%)
Max wave height (m)	0.45	0.37	17.4	0.36	0.31	16.1
Max wave power (kW/m)	0.18	0.15	17.9	0.41	0.34	19.7
Max near-bed velocity (m/s)	0.0005	0.0005	7.7	0.0007	0.0006	10.3
Max TSSC (kg/m ³)	0.0050	0.0047	6.0	0.0046	0.0044	4.3

5.00–5.45 m/s), the spatial extent of resuspension and deposition remained broadly similar. The 16–20% reduction in wave power indicates partial mitigation potential, though it is insufficient to fully suppress wave-induced sediment cycling. These findings are discussed further in the following section.

6.5 Discussion

This section synthesizes the numerical and observational results in the context of ship-generated wave-induced hydrodynamics, sediment responses, and shoreline interactions within confined, regulated waterways such as the upper St. Lawrence River. Findings are evaluated with reference to prior field and modeling work, including Haghighi et al. (2025a, 2025b) [11, 13], and broader literature on nearshore sediment dynamics.

6.5.1 Hydrodynamic Background Conditions

Nesting model, MIKE 21 HD-FM, simulations reproduced expected riverine hydraulics, including downstream gradients and localized eddies shaped by bathymetric variability. Spatial patterns in current velocity (Figures 48, 50) highlighted the role of lateral heterogeneity in generating nearshore shear zones. These outcomes align with prior studies that identified shear intensification at transitions in bathymetry [21, 153].

Concave shoreline geometry and variable slope gradients contributed to localized wave amplification, particularly at Mariatown. These effects are consistent with wave transformation dynamics reported in previous empirical and numerical investigations [16, 154].

6.5.2 Wave Prediction and Validation

Significant wave heights predicted using the VWPT and MIKE 21 SW showed strong agreement with field observations at logger sites N1 and N3 (Figures S1, S2), with deviations below 0.02 m. This confirms the suitability of the Gates and Herbich submodel for confined inland systems. The conservative but realistic wave energy magnitudes align with previous VWPT applications in estuarine and riverine contexts [21, 30].

6.5.3 Wave Propagation and Energy Distribution

Simulated wave fields exhibited energy concentration along gently sloped concave shorelines, especially at Mariatown, where significant wave height and power decreased gradually across the shelf as waves approached the shoreline (Figures 53, 54). Wave transformation was influenced by shoaling and partial reflection over irregular bathymetry, consistent with established theory [140].

While back-to-back or convoy passages were not explicitly simulated, the spatial persistence of wave energy suggests that channel geometry promotes cumulative forcing under repeated transits.

6.5.4 Near-Bed Dynamics and Sediment Response

MIKE 21/3 FM outputs showed intensified near-bed velocities along shallow shelves, particularly at locations experiencing wave convergence (Figure 57). Despite transient entrainment, cumulative bed level change remained under 0.12 mm (Figures 58, 60), consistent with short-term cohesive sediment response.

Suspended sediment concentrations (TSSC) immediately after ship passages remained below 0.005 kg/m^3 , with elevated values concentrated in nearshore regions, including but not limited to logger grid cells (Figures 62, 63). Values were extracted at the final simulation time step (step 100) for each passage, corresponding to 2,400 seconds after the initial ship-induced forcing and just before the onset of the next passage. At this point, TSSC had largely declined, indicating rapid redeposition following each event. The modeled deposition flux during this interval was approximately $4.4 \times 10^{-6} \text{ kg/m}^2/\text{s}$, equivalent to about 10 g/m^3 of sediment settled from suspension. These results support the interpretation that sediment resuspension was short-lived and spatially constrained, consistent with field observations and prior findings [11, 34, 93].

6.5.5 Representative vs. Reduced-Speed Scenarios

Two ship operating speeds were modeled: observed transits (5.45 m/s for cargo, 5.00 m/s for tankers) and a mitigation scenario at 4.00 m/s for both classes. The reduced-speed condition led to 16–17% reductions in wave height and 14–20% reductions in wave power (Table 22), confirming the role of speed in wave energy generation [13, 34]. However, the spatial distribution of sediment response remained largely unchanged. Local bathymetry and shoreline morphology remained the dominant drivers of wave convergence and resuspension zones. These findings match previous observations that ship class and draft are more predictive of sediment response than speed alone [13, 34, 93].

6.5.6 Limitations and Future Work

This study provides a validated, high-resolution modeling framework to assess the isolated impact of ship-generated waves on nearshore hydrodynamics, suspended sediment concentration (SSC), and short-term deposition in a confined fluvial system. By focusing specifically on wave-induced sediment responses, the model successfully decoupled the effects of navigation traffic from other confounding processes and demonstrated consistent agreement with observed turbidity and logger data.

Several simplifying assumptions were adopted to maintain this focus. Seasonal hydrological variability, such as spring freshet and winter low flows, was not included, and wind forcing was limited to monthly averages in the nesting model. As such, extreme wind events known to drive shoreline erosion and turbidity surges during winter and early spring were intentionally excluded. Future complementary simulations that isolate wind-only forcing may help distinguish seasonal morphodynamic processes from those induced by navigation.

The current analysis considered only one mitigation measure: reduced ship speed. This simplification was appropriate given the study’s objective to map SSC and deposition patterns under uniform synthetic ship scenarios. However, the framework developed here can be extended to test additional management strategies, including staggered vessel timing, convoy passage effects, class-specific vessel restrictions, or alternative channel alignments. Further enhancements, such as multi-layer sediment beds, dynamic roughness, vegetation damping, and full 3D wave-current coupling, could improve predictive performance in shallow, erosion-sensitive zones.

Overall, the methodology and findings presented here offer a transferable foundation for applied coastal management in regulated inland waterways and can inform future design and policy efforts aimed at mitigating ship-induced sediment stress under evolving traffic and climate regimes.

6.6 Conclusion

This study applied a nested numerical modeling framework to evaluate hydrodynamic and sedimentary responses to commercial ship-generated waves in the Upper St. Lawrence River. The approach combined domain-scale hydrodynamics (MIKE 21 HD-FM), empirically derived wave forcing using the VWPT method, and nearshore wave propagation and sediment transport modules (MIKE 21 SW and MIKE 21/3 FM).

Simulations were conducted under two scenarios: typical operating speeds (5.45 m/s for cargo vessels; 5.00 m/s for tankers) and a uniform reduced-speed scenario (4.00 m/s for both). The Gates and Herbich submodel produced representative wave inputs, validated against logger observations at two shoreline sites. The models captured localized ship generated wave propagation, shoreline energy delivery, and sediment resuspension patterns under cohesive sediment conditions.

Reducing vessel speed produced measurable declines in wave height and power (14–20%) and corresponding reductions in suspended sediment concentration. However, the spatial patterns of energy convergence and sediment response remained unchanged. These findings reinforce the dominant role of shoreline geometry, bathymetry, and cohesive substrate properties in governing localized resuspension, as also supported by empirical findings in Haghighi et al. (2025b).

The consistent activation of depositional zones in both baseline and reduced-speed simulations suggests persistent vulnerability of concave nearshore shelves. While vessel speed reductions can lower wave energy, mitigation strategies must also account for spatial heterogeneity in shoreline morphology. This supports targeted interventions such as localized speed control, shoreline stabilization, or channel reconfiguration rather than uniform system-wide constraints.

The modeling framework developed in this study offers a practical approach for evaluating sediment response under realistic vessel traffic conditions in confined waterways. Future

applications may extend the model to explore other mitigation scenarios, such as vessel class restrictions or staggered transit timing, as well as include extreme wind events, convoy passage simulations, and erosion under non-navigation conditions. These enhancements would enable a more complete understanding of long-term morphological evolution and inform adaptive shoreline management in regulated riverine systems.

7 General Discussion and Synthesis

This chapter integrates the findings of the three core studies presented in Chapters 4 through 6, providing a critical synthesis of their contributions to the understanding of ship-generated wave dynamics and sediment transport in confined inland waterways. While each chapter was designed to be self-contained and methodologically focused, the broader significance of the research emerges through their combined narrative—from empirical wave separation and field-based sediment observations, to predictive modeling of vessel impacts, and finally to high-resolution numerical simulation of long-term morphodynamic trends. This integrative perspective enables a more comprehensive evaluation of the processes governing sediment resuspension, redistribution, and shoreline vulnerability in regulated river systems such as the Upper St. Lawrence. The discussion highlights how the individual studies reinforce and extend one another, identifies emergent themes and implications, and places the results within the context of existing literature, operational decision-making, and future environmental risk scenarios.

The following sections provide a structured synthesis beginning with a summary of key findings across all three studies.

7.1 Summary of Key Findings

This dissertation presented a three-level investigation into ship-generated wave dynamics and their sedimentary consequences in the Upper St. Lawrence River. Through an integrated sequence of observational, data-driven, and numerical modeling approaches, the research offers a unified framework for isolating, quantifying, and simulating anthropogenic wave forcing in a confined, regulated inland waterway. The primary findings are synthesized here from the three core studies that form Chapters 4, 5, and 6.

7.1.1 Wave Signal Separation and Field-Based Sediment Response (Paper I)

The first study focused on disentangling ship-generated wave signals from overlapping natural disturbances using high-frequency wave and turbidity data collected at two nearshore monitoring sites. A hybrid wave decomposition framework was developed that combined frequency-domain spectral analysis, Butterworth filtering, and synthetic Gaussian-filtered reconstructions of wind and seiche signals based on calm-period PSD envelopes. This approach enabled time-localized isolation of primary (drawdown) and secondary (Kelvin) ship wave components from spectrally mixed signals, verified through synchronized video records and vessel AIS tracks.

Field results revealed that secondary ship waves were primarily responsible for abrupt, short-duration turbidity spikes—often greater than those induced by wind events. These

effects were most pronounced at Mariatown, where shallow depths, cohesive sediments, and minimal shoreline protection enhanced wave-induced resuspension. In contrast, Jacobs Island exhibited more moderate turbidity fluctuations, consistent with coarser bed material, partial protection, and greater distance from the main channel. Wind-induced waves produced more sustained but lower-magnitude turbidity increases, confirming that wind and ship waves mobilize sediment through distinct mechanisms. These results empirically demonstrated the episodic and site-specific nature of ship-induced sediment resuspension under real-world conditions.

7.1.2 Data-Driven Modeling of Ship Characteristics and Sediment Forcing (Paper II)

The second study evaluated the influence of vessel-specific parameters—such as speed, draft, length, and type—on nearshore wave energy and sediment response using synchronized field data and ship traffic records. Two modeling approaches were employed: multivariate time-lagged regression and a Long Short-Term Memory (LSTM) neural network.

Both approaches identified vessel speed and draft as the dominant predictors of wave-induced shear stress and turbidity fluctuations. Regression models provided interpretable coefficients and time-delay sensitivities, while the LSTM network improved predictive performance by learning nonlinear dependencies and memory effects across sequential events. Tankers and deep-draft cargo vessels consistently produced higher shear stress levels, often exceeding erosion-relevant thresholds at multiple monitoring stations. Furthermore, closely spaced ship passages contributed to sediment response amplification through temporal clustering effects, underscoring the importance of both vessel characteristics and traffic frequency in sediment risk forecasting.

7.1.3 Numerical Simulation of Ship Wave-Induced Sediment Dynamics (Paper III)

The final study applied the integrated numerical modeling framework available in MIKE 21/3, combining the Spectral Wave (SW) and Flow Model (FM) modules with the built-in cohesive sediment transport routines. A synthetic annual time series comprising approximately 2,500 ship passages was generated using the Vessel Wake Prediction Tool (VWPT) to simulate cumulative sediment response under operational traffic conditions, while excluding both wind wave and wind-induced current forcing to isolate ship effects.

Model outputs reproduced observed spatial patterns of significant wave height, wave power, near-bed orbital velocity, suspended sediment concentration (SSC), and net bed level change at both Mariatown and Jacobs Island. Energy convergence along concave shoreline segments and site-specific differences in sediment response were captured through nested mesh refinement and sediment transport parameterization. The model demonstrated that wave-induced sediment resuspension events under low ambient current conditions led predominantly to local redeposition near the point of entrainment. This outcome aligns with findings from prior research reviewed in Chapter 2, which indicate that under weak background flows, resuspended sediment tends not to be transported downstream, but rather settles back in place.

Although long-term morphological change was limited at the reach scale, localized erosion and deposition patterns emerged in the nearshore zone, particularly during periods of intensified ship activity. Reduced-speed scenarios in the simulations consistently resulted in lower wave forcing and diminished SSC levels near the shoreline, illustrating the potential of speed management as a viable sediment risk mitigation strategy—particularly for sensitive shoreline segments.

Together, the three studies constitute a coherent analytical progression. The wave separation methodology in Paper I enabled reliable detection of discrete ship-induced events under complex environmental conditions. Paper II translated these physical responses into statistical and machine learning models that linked vessel attributes to sediment risk. Paper III operationalized these insights into a dynamic numerical simulation framework, capturing sediment resuspension and redeposition patterns under a synthetic yet empirically grounded vessel traffic regime. The integration of high-resolution field observations, predictive modeling, and validated sediment simulations offers the first end-to-end assessments of ship-induced sediment dynamics in a regulated inland river system.

8 Conclusions and Future Work

This dissertation applied a nested modeling and analysis framework to evaluate hydrodynamic and sedimentary responses to commercial vessel traffic in the Upper St. Lawrence River. The work combined field-based signal separation of ship wakes, regression and machine learning approaches for turbidity prediction, and numerical simulations using MIKE 21 SW and MIKE 21/3 FM. These complementary approaches provided a consistent basis for examining how ship passages influence wave dynamics and sediment resuspension in a regulated riverine setting.

The results indicated that ship-generated waves contribute to recurrent resuspension events under low ambient flow conditions. Logger records showed that drawdown and secondary wave components sustained return flows and sediment suspension beyond the initial passage. Statistical and regression analysis demonstrated relationships between vessel characteristics, such as speed and draft, and the magnitude of turbidity pulses. Numerical simulations reproduced localized wave propagation and resuspension patterns and showed that speed reductions lowered overall wave energy, although spatial patterns of energy convergence and resuspension remained unchanged. Shoreline geometry, bathymetry, and substrate conditions were the primary factors shaping localized responses, in agreement with earlier field analyses (Haghighi et al., 2025b).

The findings suggest that reductions in vessel speed alone may have a limited effect in addressing shoreline vulnerability and that site-specific measures that reflect local morphology and sediment type may be required. Approaches such as localized speed zones, shoreline stabilization works, or adjustments to channel use could be considered where sensitive reaches are identified. The framework developed here can be adapted to evaluate similar questions in other large rivers and inland waterways.

Future work could extend these simulations to longer time periods to investigate cumulative patterns of erosion and deposition. Incorporating wind-wave generation and wind-driven currents would provide a better assessment of how natural and vessel-related drivers interact. Representing sediment heterogeneity, including mixtures of cohesive and non-cohesive

materials, could improve the realism of resuspension thresholds. Coupling sediment transport simulations with ecological or water quality models would also provide a basis for examining the broader system effects of turbidity pulses. Finally, applying this framework to other regulated river systems would help to evaluate its general applicability and to inform management under different geomorphic and operational contexts.

In general, this research provides a framework for studying ship-wave and sediment interactions in confined river settings and identifies several areas where future work is required to better understand long-term processes and support management decisions.

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Supplementary Material

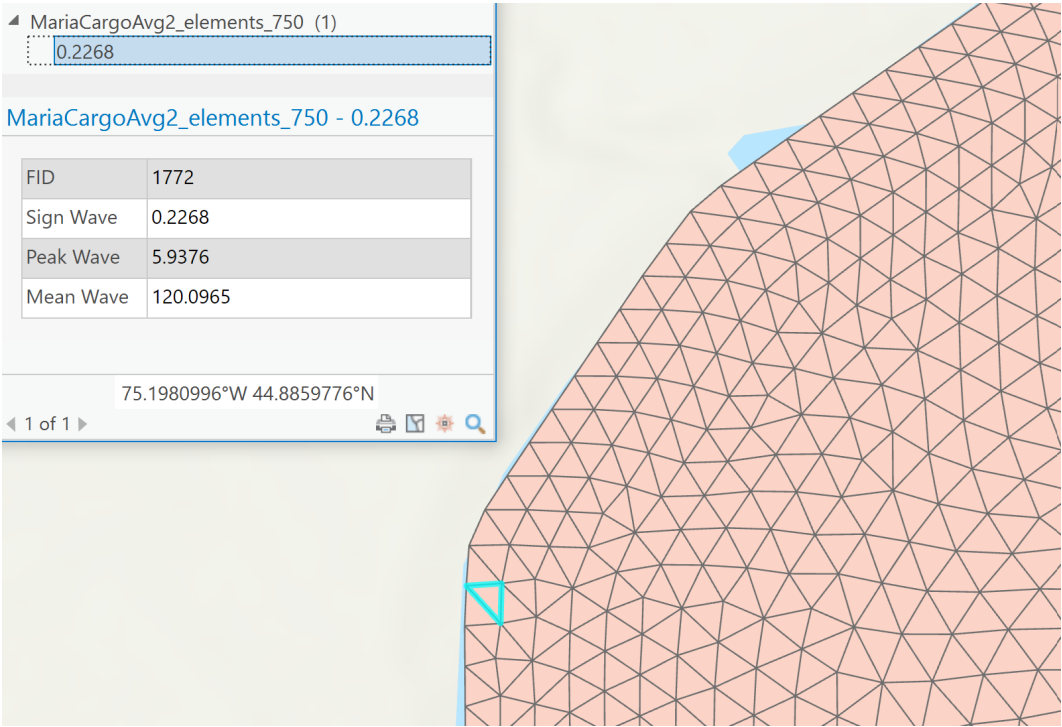


Fig. S1 Validation: Modeled vs. observed SWH at N1 logger site.

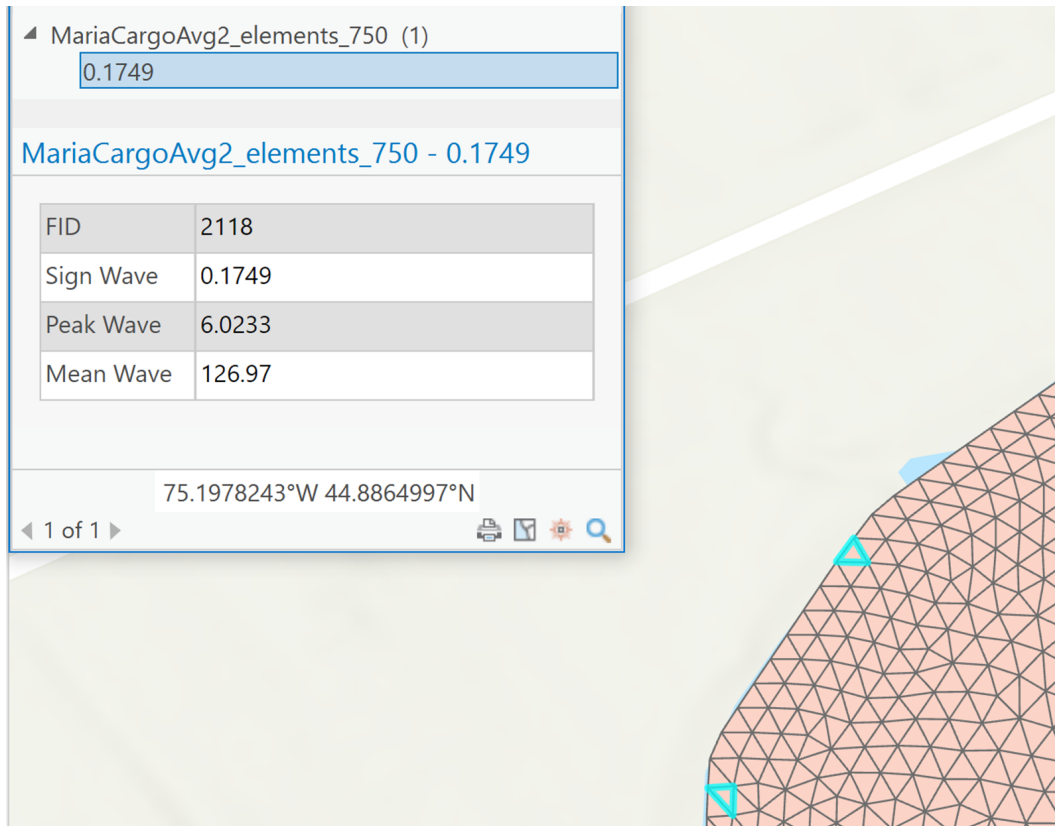


Fig. S2 Validation: Modeled vs. observed SWH at N3 logger site.

Table 1 Comparison of modeled and observed substantial wave heights.

Station	Modeled SWH (m)	Observed SWH (m)
N1	0.2268	0.210
N3	0.1749	0.180

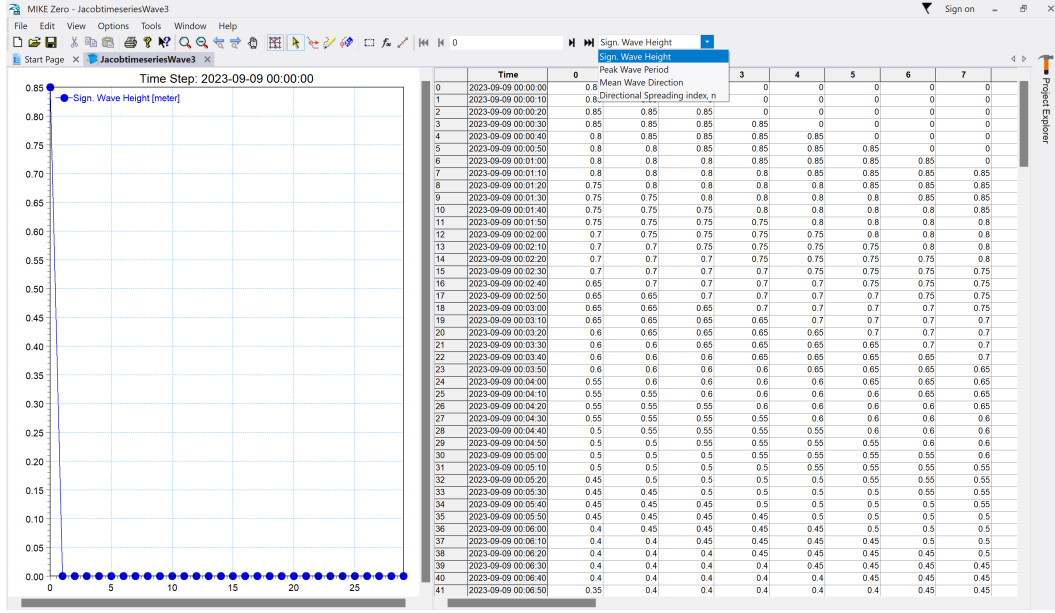


Fig. S3 Ship-generated wave input time series (WH) for MIKE 21 SW.

The bandpass filter was unsuitable for clearly distinguishing ship-generated wave and wind waves due to the frequency overlap, shown in Figure S1. This study further investigated the filter's results by exploring alternative signal processing techniques and refining the spectral analysis to improve wave separation.

Wavelet transforms conducted on the time series displayed in Figure S1 allowed analysis of transient features and time-frequency interactions between ship-generated waves and natural waves, as illustrated in Figure S2.

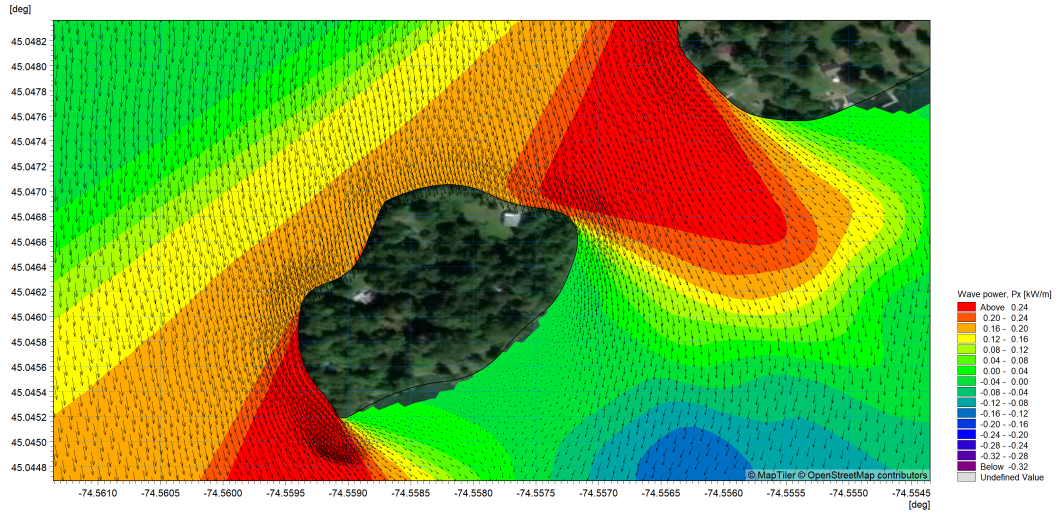


Fig. S1 A ship passage event with low wind conditions recorded by logger N1 on September 10th, 2023, analyzed using a simple high-vs-low-frequency filter. The spikes after the ship's passage in the wind wave (depicted in green) indicate that the bandpass filter causes some leakage of the ship's generated wave energy into the filtered wind wave.

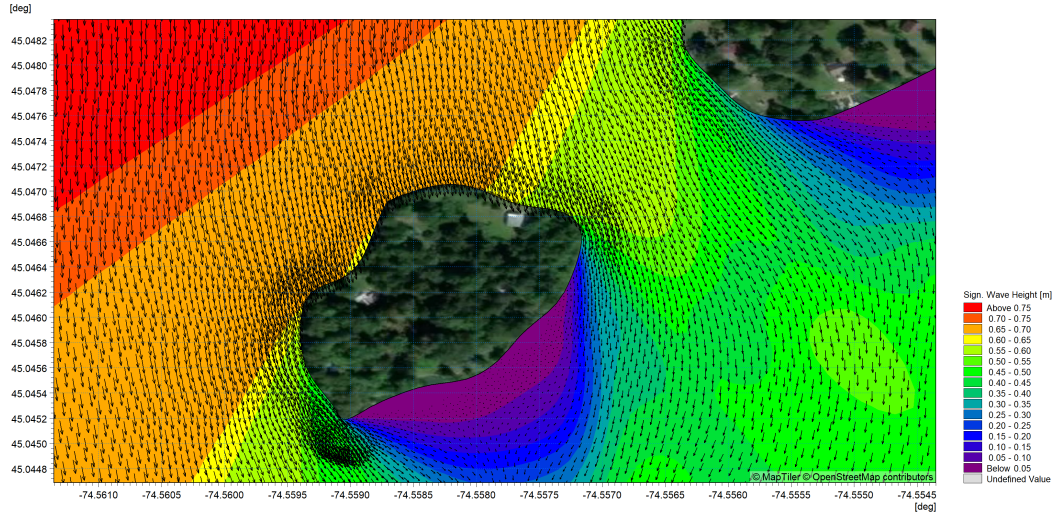


Fig. S2 Wavelet analysis on one ship event for 60 minutes: Scale 100 corresponds to a pseudo-frequency of approximately 0.0382 Hz, Scale 40 corresponds to a pseudo-frequency of approximately 0.0955 Hz, and Scale 20 corresponds to a pseudo-frequency of approximately 0.1910 Hz. The wavelet analysis effectively captures this frequency overlap and allows the temporal development of these events to be assessed individually, enabling separate quantification of their contributions to turbidity.