KERR WOOD LEIDAL
consulting engineers

Greater Vancouver
200 - 4185A Still Creek Drive
Burnaby, BC V5C 6G9
T 604 294 2088
F 604 294 2090

Technical Memorandum

DATE: February 17, 2021

TO: Spencer Taft, Cumulative Effects Project Manager
Tsleil-Waututh Nation

FROM: Eric Morris, M.A.Sc., P.Eng.
Patrick Lilley, M.Sc., R.P.Bio., BC-CESCL

RE: **Burrard Inlet Cumulative Effects Monitoring Initiative**
Central Harbour Wave Climate Study – Summary and Discussion of Findings
Our File 3454.027-300

1. Introduction

Tsleil-Waututh Nation (TWN) retained Kerr Wood Leidal Associates Ltd. (KWL) to conduct a study of the wave climate in the Central Harbour of Burrard Inlet, in front of TWN's main community ("Burrard I.R. No. 3") and at Whey-ah-wichen, a Tsleil-Waututh ancestral village site located in Cates Park in the District of North Vancouver. The study included assessment of waves generated by wind and passing vessels and consisted of the deployment of two wave measurement buoys from August 2019 to September 2020, data analysis, and reporting. Vessel wake wave occurrences were linked to vessel types so that the relative contributions of the passage of different vessel types to the overall wave climate could be determined.

The wave data collection and analysis work for this assignment was conducted by MarineLabs Data Systems Inc. (MarineLabs) based out of Victoria, BC. Details regarding the wave data collection, analysis, and findings are summarized in the MarineLabs report "Tsleil-Waututh Wave Monitoring" which is included as Attachment A. Portions of the wave data analysis conducted by MarineLabs are proprietary and confidential and therefore some sections of their report have been redacted for public distribution. KWL has conducted a review of MarineLabs' general approach and wave data results but has not conducted a detailed review of the raw wave data or data analysis.

This memorandum provides a summary of the study approach and findings and then discusses the implications of the study findings with respect to management of these impacts, including understanding the contribution of vessel wakes to shoreline erosion in the Central Harbour and potential impacts to natural shorelines and cultural sites. The study was undertaken as part of TWN's ongoing Burrard Inlet Cumulative Effects Monitoring Initiative (CEMI).

2. Study Approach and Findings

2.1 Wave Measurement

From August 2019 to September 2020, wave data were collected by two real-time wave measurement buoys deployed on the north shore of the Central Harbour. "Burrard 1" was located offshore of TWN's main community, to the east of Maplewood Mudflats, and "Burrard 2" was located offshore of Whey-ah-wichen/Cates Park, northeast of Roche Point (Figure 1). The buoy locations were selected to be outside of Port of Vancouver shipping lanes and not impede boat traffic at the boat launch and dock at Whey-ah-wichen. The two buoys where initially deployed in tandem at the "Burrard 1" site only but the second buoy was subsequently relocated to "Burrard 2" after about one month once it had been confirmed that a single buoy was sufficient for characterizing waves at a site.

The wave buoys were designed, constructed, and deployed by MarineLabs. The wave buoys were "CoastScout" units which included accelerometers, a compass, a GPS, and an ultra-sonic wind sensor that provides wind speed, direction and gust. The buoys recorded 45-minute data files every hour; the remaining 15 minutes of each hour were used to transmit the data to a cloud server via cellular telemetry. The sample rate of the motion data was 5 Hz and the sample rate of the wind data was 2 Hz.

2.2 Wave Data Analysis

MarineLabs also performed the wave data post-processing and analysis and developed algorithms to separate vessel wake wave measurements from wind wave measurements and link wake wave events to Automatic Identification System (AIS) vessel tracking data.

Detection of Vessel Wake Events from Wave Measurement Data

MarineLabs developed a proprietary algorithm to analyse the time series data collected by the wave buoys and separate vessel wake waves from wind-generated waves. They developed and applied an uncertainty analysis, and found that, for the conditions at the sites in Burrard Inlet, the wave data could be processed to identify discrete vessel wake events with an approximate 79% success rate. Most errors in the wake detection algorithm were found to be due to missed wake events and, therefore, the wake detection algorithm tends to underestimate the amount of wake activity. This observation was used to establish lower and upper bounds for vessel wake occurrence probabilities.

Linking Vessel Wake Events to Specific Vessel Types

Once individual vessel wake events were identified, further analysis was undertaken to link these events to specific vessel types such that the relative contributions of the passage of different vessel types to the overall wave climate could be determined. This task was completed by developing a further algorithm to link vessel wake wave events to specific vessels passing by the buoys as recorded in vessel tracking data.

The Automated Identification System (AIS) is a vessel tracking system that uses transceivers on vessels to provide vessel locations and status details to aid in collision avoidance. However, AIS data can also be obtained to study vessel behaviour and compile statistics. AIS data is transmitted by large commercial vessels as well as some smaller vessels. The International Maritime Organization (IMO) mandates the use of AIS in vessels larger than 300 gross tonnes that travel internationally. AIS data includes, among other things, information on vessel position, speed, heading, ship identification (number, name, radio call sign), vessel type, dimensions and draft. For this study, AIS data was obtained from MarineTraffic, an online vessel tracking data provider (www.MarineTraffic.com), at a 2-minute sampling rate using an application programming interface which allowed MarineLabs to automate the data download and storage in a format that facilitated automated analysis.

In addition to the AIS data, periodic visual observations of vessel transits past the buoys were made and used to verify the AIS data and capture a representative subset of vessel wake wave events caused by non-AIS tracked vessels.

Comparing Wave Power of Different Vessel Types and Vessels vs. Wind-generated Waves

Wave power was selected as the fundamental measure of the wave climate for this study. Wave power was selected because shoreline erosion is a primary concern of TWN and studies have indicated that wave power and shoreline erosion rates can be correlated[1,2]. In particular, the wave data was analyzed in terms of the “wave power exceedance probability”, which gives an indication of the proportion of time that wave power levels are greater than a certain value.

The wave power exceedance probabilities were looked at in two different ways:

- **Joint Probabilities** were examined in order to assess the relative contributions to the overall wave power climate of wind generated waves and vessel wakes.
- **Conditional Probabilities** were examined in order to assess the relative contributions of various vessel types to the vessel wake climate.

2.3 Summary of Key Findings

The key findings of this wave climate study can be summarized as follows:

1) The results show that high-resolution wave monitoring data can be used to successfully identify discrete wave events caused by vessel wakes. The algorithm developed was successful in identifying a high percentage of wave events caused by vessel transits past the buoys.
2) At both sites, vessel wake waves were consistently distinguishable from wind waves and were shown to increase the overall wave energy beyond that of the natural wind-generated wave environment.
3) The probability of wave power levels exceeding specific thresholds was greater due to the addition of vessel wakes, with the increase in probability ranging from 1.2 to 4.6 times depending on the site and threshold. For example, at Burrard 1, vessel wakes increase the probability of wave power exceeding 100 W/m by approximately 1.2 times. At Burrard 2, the increase in probability is 2.3 times.
4) At the Burrard 2 site, high wave power level events were more likely to be caused by vessel wakes. At the Burrard 1 site, high wave power level events were more likely to be caused by wind-generated waves.
5) At both sites, of the vessel wake wave events captured, wakes from vessels with no AIS data were recorded most frequently. The next most common vessel wake recorded was from Tugs followed by AIS-equipped Passenger and Pleasure Craft. Vessels with no AIS data make up 63% of the observed vessel wakes at the Burrard 1 site and 85% of the observed vessel wakes at the Burrard 2 site. Tugs make up 20% of the observed vessel wakes at the Burrard 1 site and 9% of the observed vessel wakes at the Burrard 2 site. AIS-equipped Passenger and Pleasure Craft make up 11% of the observed vessel wakes at the Burrard 1 site and 4% of the observed vessel wakes at the Burrard 2 site.

[1] K. L. Huppert, J. T. Perron, and A. D. Ashton, “The influence of wave power on bedrock sea-cliff erosion in the Hawaiian islands,” Geology, vol. 48, no. 5, pp. 499–503, 2020, doi: 10.1130/G47113.1.

[2] N. Leonardi, N.K. Ganju, and S. Fagherazzi, “A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes”, Proceedings of the National Academy of the Sciences of the United States, Vol 113, no. 1, pp. 64-68, January 5, 2016.

6) There is a pronounced seasonality to the passage of vessels with no AIS data, with approximately three times more traffic happening in the summer months relative to the winter months. This seasonality is also apparent for AIS-equipped Pleasure Craft.

3. Implications for Management

This study has documented that the presence of vessel wake waves has significantly increased the wave energy offshore of the study sites relative to natural "background levels". This is an important finding which validates TWN's observations over several decades. In addition, this finding has significant implications with regard to the approach to impact assessments which consider changes in vessel traffic. These impact assessments have historically been conducted on a project-by-project basis and therefore only consider the effect of incremental changes in vessel traffic, which may be small. However, assessments conducted in this manner fail to assess the cumulative effects of vessel wake contributions to the wave climate in the Central Harbour. In order to fully assess the impacts of vessel wakes, impact assessments and regulatory agencies should consider the cumulative effects of all vessel traffic, which this study has shown to be non-negligible. Furthermore, wake wave impact assessments that focus primarily on wave heights do not capture the overall impact that vessel wakes have on the wave climate, and therefore assessments should consider wave energy and power.

TWN members have been long concerned about the impacts of vessel wakes to shoreline erosion along natural shorelines and within sensitive cultural sites. TWN has observed shoreline erosion within the study area, including at their current main community ("Burrard I.R. No. 3") and at Whey-ah-wichen, for decades. This has already impacted important parts of TWN's land and several cultural sites. For example, in December 2012, several cubic meters of shoreline eroded in direct vicinity of the study area and impacted a TWN ancestral village site, exposing many cultural artifacts. This area is of extremely high cultural significance to the Nation and continues to be threatened by shoreline erosion today.

Although the specific wave power levels at which shoreline erosion is triggered are highly site-specific and are not currently known for the study area, it has been shown that changes in wave climate can disrupt the geomorphic equilibrium of shorelines, thereby resulting in changes in shoreline morphology and erosion[3]. Further study will be required to establish a definitive linkage between vessel wakes and erosion in the study area; however, the findings of this study provide evidence to corroborate TWN's strong perception that vessel wakes are a significant contributor to the shoreline erosion they have observed.

The following opportunities have been identified for the study findings to inform current policies and guidelines regarding Port and shoreline developments and management of vessel traffic in Burrard Inlet:

- There is a need for project proponents, federal and provincial regulators, and the Port Authority to recognize vessel wake as a potential impact during project assessment processes, and to ensure these impacts are appropriately quantified, assessed, and monitored.
- Vessel wake impacts must be considered within the context of cumulative effects and overall vessel traffic, rather than vessel traffic related to individual projects.
- Relevant agencies should consider policies that mitigate vessel wake impacts, such as vessel slowdowns, speed limits, shipping lane changes, exclusion zones, or other measures. These policy discussions should consider both recreational and commercial vessels.

[3] P. D. Komar, "Beach processes and sedimentation. 2nd edition", Prentice Hall, 1998.

- The potential for ship design changes, such as changes to the hull designs, that minimize wake generation at slow to moderate speeds could be examined.
- Erosion protection and mitigation designs should consider vessel wake wave effects.

4. Recommendations

This study has produced a robust and comprehensive data set of the wave climate offshore of TWN's main community in Burrard Inlet and at Whey-ah-wichen over the course of an approximately one-year period. The study has provided data on relative wave power contributions of wind waves and wake waves generated by different vessel types. To build further understanding of wave conditions and the potential contribution of vessel wakes to shoreline erosion, the following additional follow-up studies and actions are recommended:

1. Conduct studies of shoreline erosion and sediment dynamics in Burrard Inlet, including sediment transport modelling, to better understand the extent and potential causes of the observed shoreline erosion.
2. Implement a detailed shoreline monitoring program which could include ground or remote sensing surveys to document locations and rates of erosion.
3. Conduct detailed morphodynamic modelling of specific locations on TWN's shoreline using XBeach or CSHORE software to establish a better understanding of the relationship between wave power levels and rates of erosion.
4. Deploy wave buoys at additional locations within TWN's broader traditional territory to further document potential changes in wave climate due to vessel traffic.

In addition, the following opportunities have been identified for the study findings to inform current policies and guidelines regarding Port and shoreline developments and management of vessel traffic in Burrard Inlet:

- Recognize the measurable and significant contribution of vessel wakes to the wave climate in Burrard Inlet and ensure they are appropriately considered as a potential project-specific and cumulative effect during project reviews and impact assessments.
- Ensure that general pathways of effects models for marine shipping include the contribution of vessel wakes to shoreline erosion as a mechanism of effect on biophysical and cultural resources.
- Explore policy options for mitigation such as vessel slowdowns, speed limits, shipping lane changes, exclusion zones, changes to hull design, or other measures.
- Consider vessel wake waves in the design of erosion protection and mitigation options for vulnerable shorelines.

KERR WOOD LEIDAL ASSOCIATES LTD.

Prepared by:

PROFESSIONAL ENGINEER PROVINCE OF BRITISH COLUMBIA E.R. MORRIS # 28180
2021-02-17

Eric Morris, M.A.Sc., P.Eng.
Senior Coastal Engineer

Reviewed by:

Patrick Lilley, M.Sc., R.P.Bio., BC-CESCL
Senior Biologist and Project Manager

EM/pl

Encl.: Attachment A – Tsleil-Waututh Wave Monitoring Report by MarineLabs, January 27, 2021

Statement of Limitations

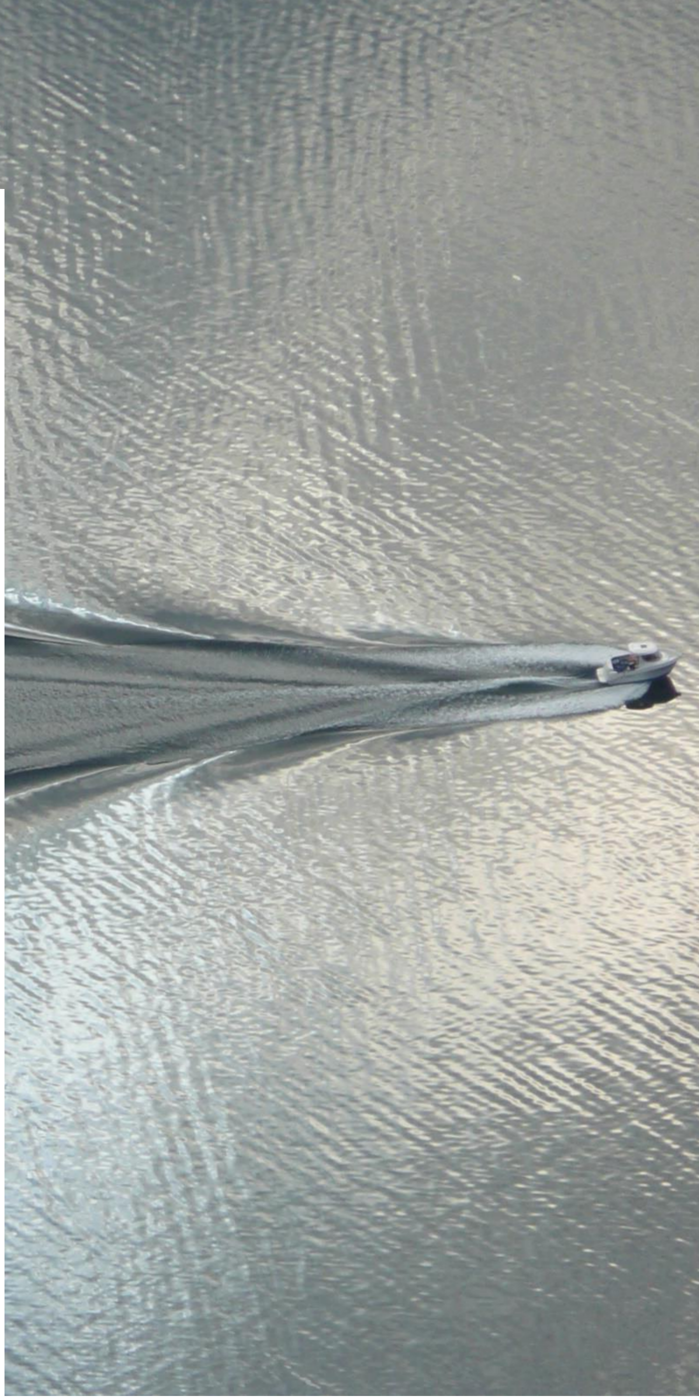
This document has been prepared by Kerr Wood Leidal Associates Ltd. (KWL) for the exclusive use and benefit of the intended recipient. No other party is entitled to rely on any of the conclusions, data, opinions, or any other information contained in this document.

This document represents KWL's best professional judgement based on the information available at the time of its completion and as appropriate for the project scope of work. Services performed in developing the content of this document have been conducted in a manner consistent with that level and skill ordinarily exercised by members of the engineering profession currently practising under similar conditions. No warranty, express or implied, is made.

Copyright Notice

Revision History

Revision #	Date	Status	Revision Description	Author
1	February 17, 2021	FINAL	Revised date on title page of MarineLabs Report	EM/PL
0	January 28, 2021	FINAL		EM/PL



Tsleil-Waututh Wave Monitoring

JANUARY 27, 2021

MarineLabs Data Systems Inc.
Scott Beatty, PhD
Bryce Bocking, MASc
Revision 4.1
Approved for Public.

MarineLabs

Executive Summary

MarineLabs was contracted by Kerr Wood Leidal Associates to provide ocean wave monitoring and vessel wake analysis services in support of Tsleil-Waututh Nation's ongoing cumulative effects monitoring program in Burrard Inlet in Greater Vancouver, BC, Canada. MarineLabs cell-network connected wind and wave monitoring buoys were deployed at two locations in Burrard Inlet from August 2019 through Sept 2020. The first location, Burrard 1, is offshore of TWN's main reserve in North Vancouver, and the second location, Burrard 2, is located NE of Roche Point off Whey-ah-whichen/Cates Park. AIS data from the relevant domain were obtained concurrently with the wave data. The buoy data was analyzed to determine the overall wave climate, the contribution of vessel wakes to the wave climate at each location, and the contribution to the wave climate from different vessel types. The project showed that in sheltered environments like Burrard Inlet, vessel wakes can be successfully identified with buoy data, and linked to AIS tracked vessels. Results indicate that at Burrard 1, high wave power levels are more often generated by wind waves than vessel wakes; However, for Burrard 2, high wave power levels are more often from vessel wakes than wind waves.

Table of Contents

Executive Summary 2
1 Background 5
1.1 Locations 5
1.2 Buoy Technology 6
2 Methodology 7
2.1 Monitoring Details 7
2.2 Wave Definitions 8
2.3 Vessel Wake Theory 9
2.4 Vessel Wake Detection 10
2.4.1 Detection method 10
2.4.2 Error analysis 11
2.5 AIS Data 12
2.6 AIS Data Linking with Wake Detection 13
3 Results 14
3.1 General Wave Climate 14
3.2 Wave Power Exceedance Probability Distributions 15
3.3 Power Exceedance Probability due to Wakes 17
3.4 AIS Wake Link 22
Conclusions 29
References 30

List of Tables

Table 1: Confidence level criteria for manually detected wakes 11
Table 2: Automatic wake detection performance summary using Burrard 2 data from 2020/03/27 to 2020/03/30. 12
Table 3: Increase in the overall probability of wave power exceeding various power levels due to wakes 21
Table 4: Monthly wake occurrences per AIS vessel type for Burrard 1 22
Table 5: Monthly wake occurrences per AIS vessel type for Burrard 2 22

Table of Figures

Figure 1. Buoy locations. Burrard 1 is located offshore of TWN's main reserve in North Vancouver. Burrard 2 is located NE of Roche Point off Whey-ah-wichen/Cates Park. 6
Figure 2. MarineLabs CoastScout buoys deployed at the sites. (left) older generation, (right) current generation CoastScout. 7
Figure 3. An illustration of the superposition of ocean waves. Monochromatic propagating waves, 8
Figure 4. Vessel wake diagram showing divergent and transverse waves with wave cusp line angle at 35^o from direction of vessel motion [2]. 10
Figure 5. Wave climate summaries for Burrard 1 (above), Burrard 2 (below) 14
Figure 6: Wave power probability of exceedance for Burrard 1 and 2 buoys. Top: wave power axis is logarithmic. Bottom: probability of exceedance axis is logarithmic 16
Figure 7: Wave power probability of exceedance distributions using the time intervals of automatically and manually detected wake events. 18
Figure 8: Burrard 1 probability of exceedance distributions for wakes and wind/background noise. The wake upper bound and wind/background noise lower bound are estimated from the automatic wake detection uncertainty analysis. The total probability distribution for all waves is also included. Top: full range of distributions. Bottom: zoomed to illustrate the uncertainty bounds at low power levels. 19
Figure 9: Burrard 2 probability of exceedance distributions for wakes and wind/background noise. The wake upper bound and wind/background noise lower bound are estimated from the automatic wake detection uncertainty analysis. The total probability distribution for all waves is also included. Top: full range of distributions. Bottom: zoomed to illustrate the uncertainty bounds at low power levels. 20
Figure 10: Fractions of the total probability of exceedance distributions for Burrard 1 and 2 that are attributed to wakes and wind/background noise. The three power levels for which the probabilities of exceedance are calculated are 50, 100 and 200 W/m. 21
Figure 11: Wake occurrence histograms for Burrard 1 and 2 23
Figure 12: Burrard 1 wave power probability of exceedance distributions based on AIS vessel type. 24
Figure 13: Burrard 2 wave power probability of exceedance distributions based on AIS vessel type. 25
Figure 14: Burrard 1 conditional probability of exceedance distributions based on AIS vessel type. 26
Figure 15: Burrard 1 conditional probability of exceedance distributions based on AIS vessel type. 27
Figure 16: Conditional probability of wave power exceeding 50 W/m for vessel wakes at Burrard 1 and 2. 27
Figure 17: Conditional probability of wave power exceeding 100 W/m for vessel wakes at Burrard 1 and 2. 28
Figure 18: Conditional probability of wave power exceeding 200 W/m for vessel wakes at Burrard 1 and 2. 28

1 Background

Tsleil-Waututh Nation (TWN) contracted Kerr Wood Leidal Associates (KWL), to support their ongoing cumulative effects monitoring program in Burrard Inlet. As part of that program, there was an identified concern about erosion of sensitive sites and habitats, and a need to understand the relative energy inputs of vessel-generated wakes compared to wind driven waves. To date, no known vessel wake measurements had been taken in the region. As a result, KWL approached MarineLabs with the opportunity to measure waves and undertake the challenge of detecting and measuring vessel wake in comparison to background wind-generated waves. MarineLabs accepted the challenge and joined the working group with TWN and KWL. The group identified and decided on potential locations that would meet the constraints of proximity to the sensitive sites while being acceptably away from any operations that affect Port of Vancouver and other marine activity.

1.1 Locations

Locations were selected in close proximity to shore to avoid causing hazards to marine traffic, to measure the wave environment close enough to the sensitive sites, and far enough away from shore that the moored buoy would not be affected by low tide. Once approvals were obtained by TWN and from Vancouver Fraser Port Authority, the buoys were deployed.

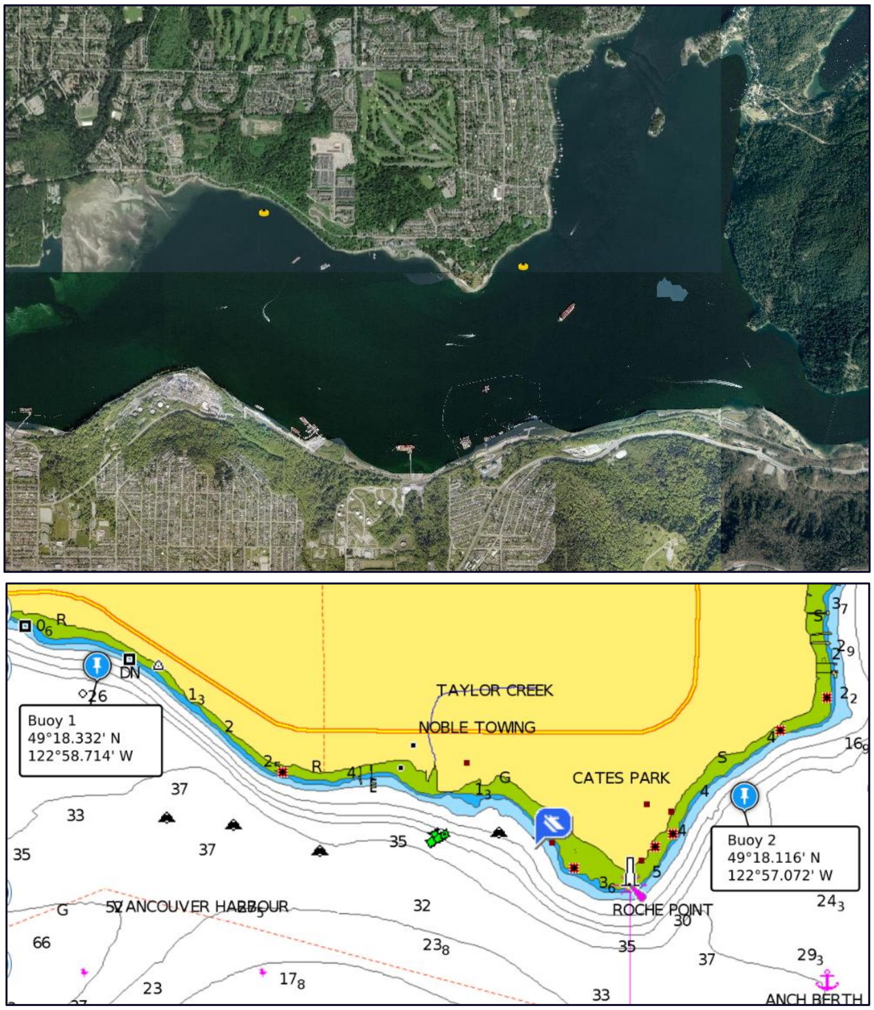


Figure 1. Buoy locations. Burrard 1 is located offshore of TWN's main reserve in North Vancouver. Burrard 2 is located NE of Roche Point off Whey-ah-wichen/Cates Park.

The monitoring locations were selected by the planning team guided by the knowledge of TWN. Early in the project, there was concern that vessel wakes may be difficult to detect with individual buoys at a site. So, in the first month of the project, two MarineLabs buoys were placed at site 1. However, after one of the buoy mooring systems was damaged, one of the buoys drifted off station and was recovered by TWN. It was realized at that stage with preliminary analysis, that wake detection was successful with a single buoy at a location, so at the next visit for field operations the final buoy locations shown in Figure 1 were established.

1.2 Buoy Technology

The buoys deployed were MarineLabs in-house developed CoastScout units. They are compact, easy-to-deploy, and transmit all their data by cell network to MarineLabs interactive browser-based platform. Wave and summary parameter data is accessible by the project team using a web browser while the high-resolution data was retrieved by the MarineLabs team directly from the cloud servers for the customized vessel wake analysis.

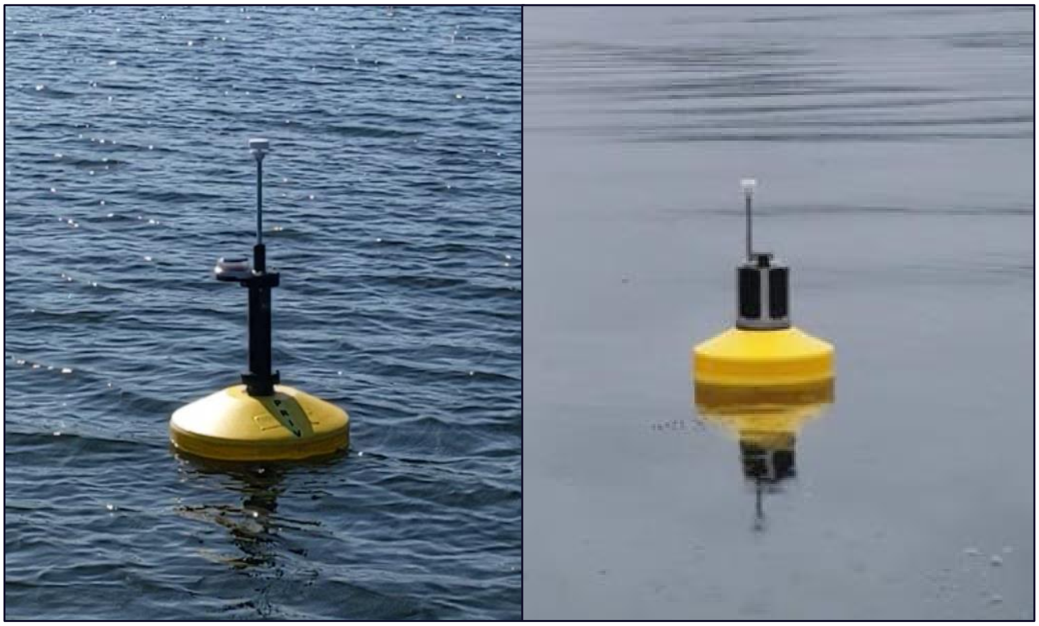


Figure 2. MarineLabs CoastScout buoys deployed at the sites. (left) older generation, (right) current generation CoastScout.

The buoys use a combination of acceleration, rotational rates, magnetic compass, and GPS for motion measurements that all combine to output buoy position timeseries that are accurate to 2cm in wave periods from 1 to 25sec. They are 60cm diameter, weigh <20kg, feature a navigation light, ultra-sonic wind sensor that provides wind speed, direction and gust. They were deployed using 3:1 scope mooring lines of 5/16” sinking line and chain sections to ensure that no vessel propellers are fouled by the mooring lines.

2 Methodology

2.1 Monitoring Details

The CoastScout signals logged were:

- Motion: acceleration, velocity, position, rotational position, rotational velocities, compass
- Wind speed, gust, wind direction, air temperature.
- GPS (latitude, longitude)

Every hour the buoys recorded 45-minute data files. The remaining 15 minutes of each hour were used to transmit the data to the cloud. The sample rate of the motion data is 5Hz and the sample rate of the wind data is 2Hz.

Because the CoastScout is so small and light, it has no motion resonances in the region of the wind-generated or wake waves. Thus, the CoastScout's vertical (z) direction motion time series is accurately applied as a proxy measurement of the water surface elevation signal. The z direction of buoy motion timeseries provides the basis for all the analysis to follow.

2.2 Wave Definitions

The wavy surface of the sea can be described mathematically as the sum, or superposition, of multiple wave systems of various amplitudes and frequencies.

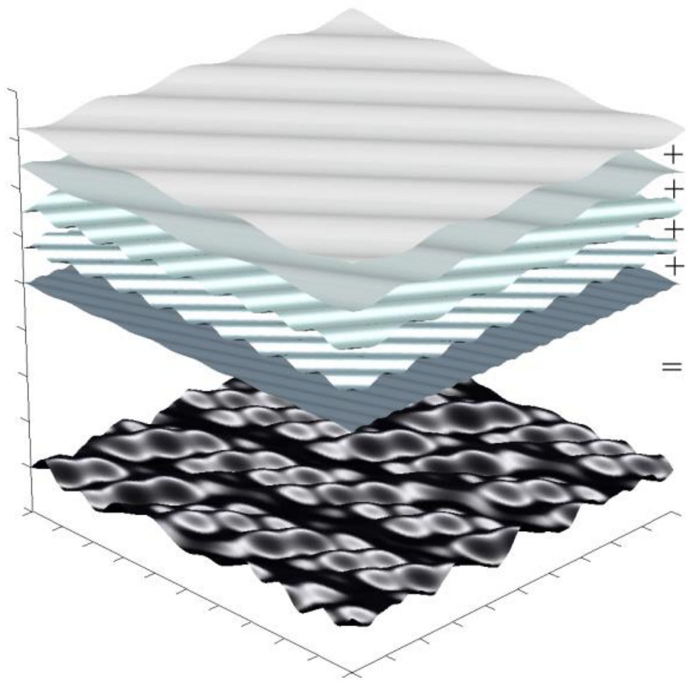


Figure 3. An illustration of the superposition of ocean waves. Monochromatic propagating waves, shown by the lightly shaded stacked surfaces, of different amplitudes, frequencies, and directions can be superposed to represent the ocean surface shown as the heavily shaded bottom surface.

Using water surface elevation measurements at a single point on the sea surface, the distribution of energy as a function of frequency, f is defined as $\rho g S(\mathrm{f})$, where $S(\mathrm{f})$ is known as the *variance density spectrum*. By removing the constants, it is the distribution of sea surface *variance* as a function of frequency.

Significant wave height H_s is defined as the average height of the highest one-third of waves within a wave record. Statistical details can be found in [1], but the spectral estimate of H_s used widely is:

$$H_s = 4\sqrt{\sum_{i}^{N} S(f)_i \Delta f_i}$$

Peak period, T_p , is defined at the wave period at which $S(\mathrm{f})$ is maximum. Also, $T_p = \frac{1}{f_p}$, where f_p is the frequency in Hz, at which $\mathrm{S}(\mathrm{f})$ is a maximum.

The summary parameters, H_s and T_p, are typically used to communicate sea characteristics and climates i.e. ECCC weather forecasts, data buoys, and in general all operational oceanographic systems.

Finally, ocean waves propagate pulses of energy across waterways. Wave energy per unit time is defined as wave power transport and denoted here as P in units of [W/m] and calculated as follows:

$$\mathrm{P} = \rho\mathrm{g} \sum_{i}^{N} S_i(f) c_g(f_i) \Delta f_i$$

where, $c_g(f_i)$ is the group velocity and may be calculated as a function of frequency based on the water depth [1]. Using a moving window of time, sliding across the entire water surface elevation time series, we can calculate $S(f)$ for each windowed time period, and we calculate wave power level time series as:

$$\mathrm{P(t)} = \rho\,\mathrm{g} \sum_{\mathrm{t_i - T_w}}^{\mathrm{t_i + T_w}} \mathrm{S_i(f) c_g(f_i) \Delta f_i}$$

Where $\mathrm{S_i}(f)$ is the spectrum using a segment of time series data of length T_w centered at t_i.

2.3 Vessel Wake Theory

Ocean waves generated by most vessels are made up of the superposition of multiple wave systems. For typical vessels, the predominant wave systems are the transverse wave systems travelling in the direction of the vessel and the divergent waves propagating at oblique angles from the direction of vessel velocity.

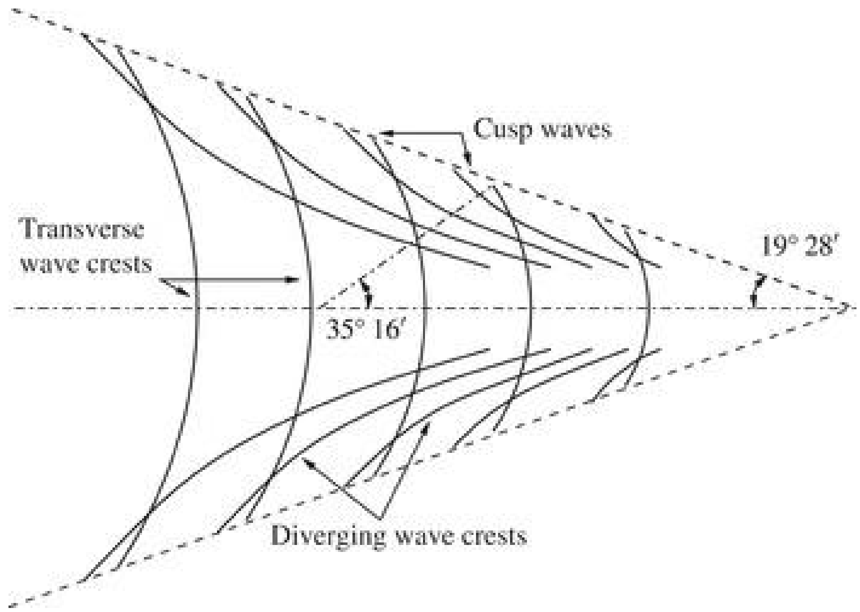


Figure 4. Vessel wake diagram showing divergent and transverse waves with wave cusp line angle at 35^o from direction of vessel motion [2].

The superposition of the two wave systems creates a larger wave system known as the *cusp waves*, that propagate at an angle of 35.3 degrees from the vessel direction of travel [2]. In this work, we build the analysis using geometry of the cusp and diverging wave systems.

2.4 Vessel Wake Detection

MarineLabs has developed a proprietary vessel wake detection algorithm and has applied the algorithm to develop the results in this study.

2.4.1 Detection method

By applying the MarineLabs' detection algorithm, the start and stop times of the vessel wakes can be recorded within the buoy surface elevation timeseries. The interval between start and stop times is flagged as a *wake event*.

By iterating this procedure over all the observations for both buoys over the year, wake event statistics in terms of occurrence, height, and power level are calculated.

2.4.2 Error analysis

To check the effectiveness of the wake detection procedure, a manual "human in the loop" process was undertaken. Because the valid wakes are quite easy for a human analyst to successfully determine, the comparison of automated wake detection to human wake detection was undertaken for a sample of 72 hours.

Wakes were manually detected using Burrard 2 data from 2020/03/27 to 2020/03/30. The start time, end time and confidence level for each wake event was recorded. Confidence level criteria levels were defined as follows (1 is lowest confidence and 5 is highest):

Table 1: Confidence level criteria for manually detected wakes

1	Wake is faintly visible but the shape is disorganized.
2	Wake is faintly visible, but the shape is slightly organized.
3	Wake is visible but the shape is disorganized, possibly due to multiple overlapping vessel wakes.
4	Visible increase in wave height in the heave time series. The wake is visible and moderately organized.
5	Large increase in wave height in the heave time series. The wake is visible and strongly organized.

Criteria for automated vs. manual wake detection were:

- If at least 1 automatically detected wake event falls within the start and end times of a manually detected wake, it is considered ***detected.***
- If no automatically detected wakes fall within the start and end times of a manually detected wake, it is considered ***missed.***
- If an automatically detected wake does not fall within the start and end times of a manually detected wake, it is considered a ***false positive.***

A summary of the wake detection error analysis results is given in Table 2.

Table 2: Automatic wake detection performance summary using Burrard 2 data from 2020/03/27 to 2020/03/30.

Confidence Level	Detected	Missed
1	24	20
2	32	7
3	40	2
4	11	0
5	6	0
Total	**113**	**29**
False Positives	**5**	

Table 2 indicates that out of a total of 142 wake events, 113 were detected automatically, 29 missed, and 5 were false positives. Thus, out of the 142 wake events, over the three-day period, there was a 79% success rate. Note that most errors in the wake detection algorithm are due to missed wake events. Therefore, the automated wake detection algorithm tends to underpredict the amount of wake activity. This observation is used in Section 3.3 to establish lower and upper bounds for the wave power probability of exceedance due to vessel wakes.

2.5 AIS Data

Automatic Information System (AIS) data provides domain awareness of all large commercial vessels as well as some smaller vessels. The system provides helpful vessel locations and status details for rescue operations. AIS data can also be obtained to study vessel behavior and compile statistics about that behavior over time. AIS data includes:

- Vessel Maritime Mobile Service Identity (MMSI)
- Navigation status: E.g., "at anchor", "under way using engine(s)", "not under command", etc.
- Rate of turn: right or left, from 0 to 720 degrees per minute
- Speed over ground: 0.1-knot (0.19 km/h) resolution from 0 to 102 knots (189 km/h)
- Positional accuracy:
    - Longitude: to 0.0001 arcminutes
    - Latitude: to 0.0001 arcminutes
- Course over ground: relative to true north to 0.1°
- True heading: 0 to 359° (for example from a gyro compass)
- True bearing at own position: 0 to 359°
- UTC seconds: The seconds field of the UTC time when these data were generated. A complete timestamp is not present.

- IMO ship identification number
- Radio call sign
- Name
- Vessel Type
- Dimensions of ship, to nearest meter
- Draught of ship: 0.1–25.5 meters
- Destination: max. 20 characters
- ETA (estimated time of arrival) at destination: UTC month/date hour:minute

A reliable, high resolution AIS data source was necessary for this project. After some research and attempts to find sources available to TWN at no cost, it was determined that the data will be purchased using a monthly subscription from MarineTraffic.com. The benefit of this approach was the data was available at 2 minute update rates (their maximum), and available using an API which allowed MarineLabs to automate the download and storage programmatically in a format that facilitated automated analysis in this project. The bounding box of the AIS data region in Burrard Inlet is:

Longitude max:	-122.812485
Longitude min:	-123.146194
Latitude max:	49.476472
Latitude min:	49.271371

2.6 AIS Data Linking with Wake Detection

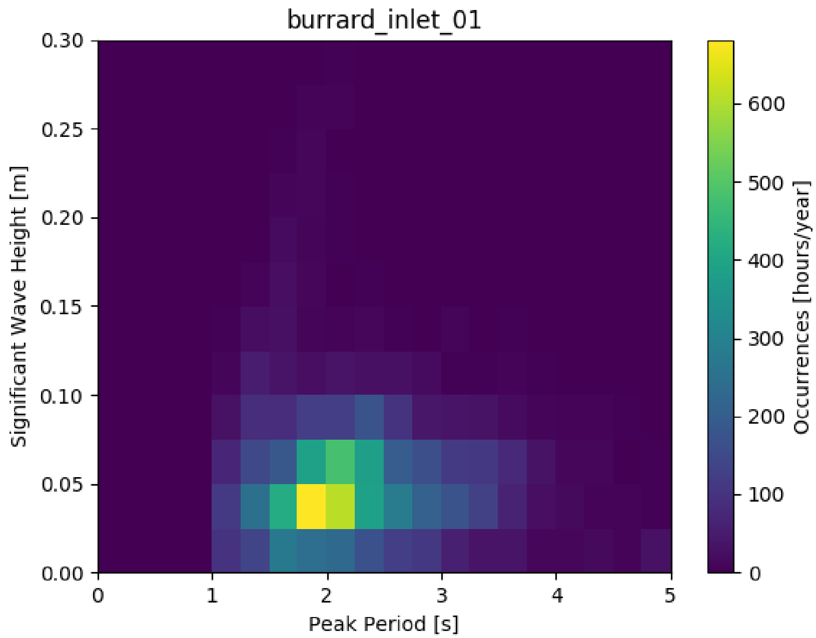
The CoastScout buoy locations are within the AIS data bounding box, and both the buoy data and AIS data are referenced to GPS time, which means no time corrections or synchronization issues were encountered.

At each buoy, for every vessel transit through the domain, a MarineLabs proprietary calculation was iterated with automated scripts. The detected wakes that are *linked* with AIS vessel transit events allow an analysis on the statistics of vessel wake occurrence, height, power level by vessel type or any other AIS provided data.

3 Results

3.1 General Wave Climate

The overall wave climate (including wind waves and vessel wake) in terms of occurrences as a function of significant wave height and peak period for each location are shown here. The wave climates at both locations are similar, with the greatest number of sea state occurrences at both locations having significant wave heights between 2.5 and 5cm and peak periods between 1.75 and 2 seconds.



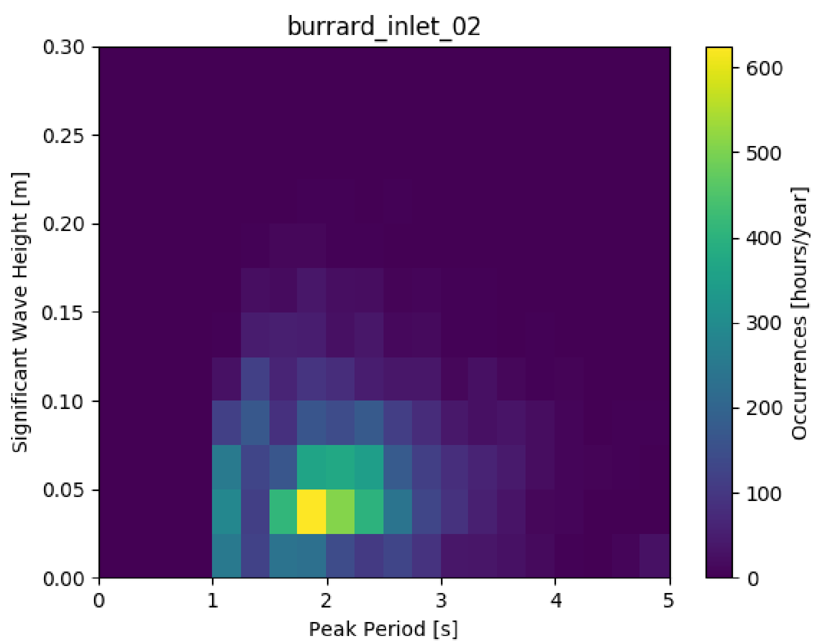


Figure 5. Wave climate summaries for Burrard 1 (above), Burrard 2 (below)

3.2 Wave Power Exceedance Probability Distributions

Wave power probability of exceedance curves are valuable for coastal cumulative effects monitoring because shoreline erosion is related to wave power levels [4]. To create these curves, buoy heave time series data is first converted to wave power time series using the method described in Section 2.2. The wave power time series is then converted to a power exceedance probability distribution by counting the number of data points that exceed a given power level. Figure 6 shows the overall wave power probability of exceedance distributions for each location. Two representations of the distributions are presented to better observe differences between the two distributions at low and high wave power levels.

The results in Figure 6 indicate there are subtle differences in the overall wave climates at Burrard 1 and Burrard 2. Low wave power levels (less than 50W/m) occur more frequently at Burrard 2, possibly due to more exposure to wind. In addition, high wave power levels (greater than 250 W/m) occur more frequently at Burrard 2. Whether or not these higher power levels are attributed to vessel wakes is investigated in Section 3.3.

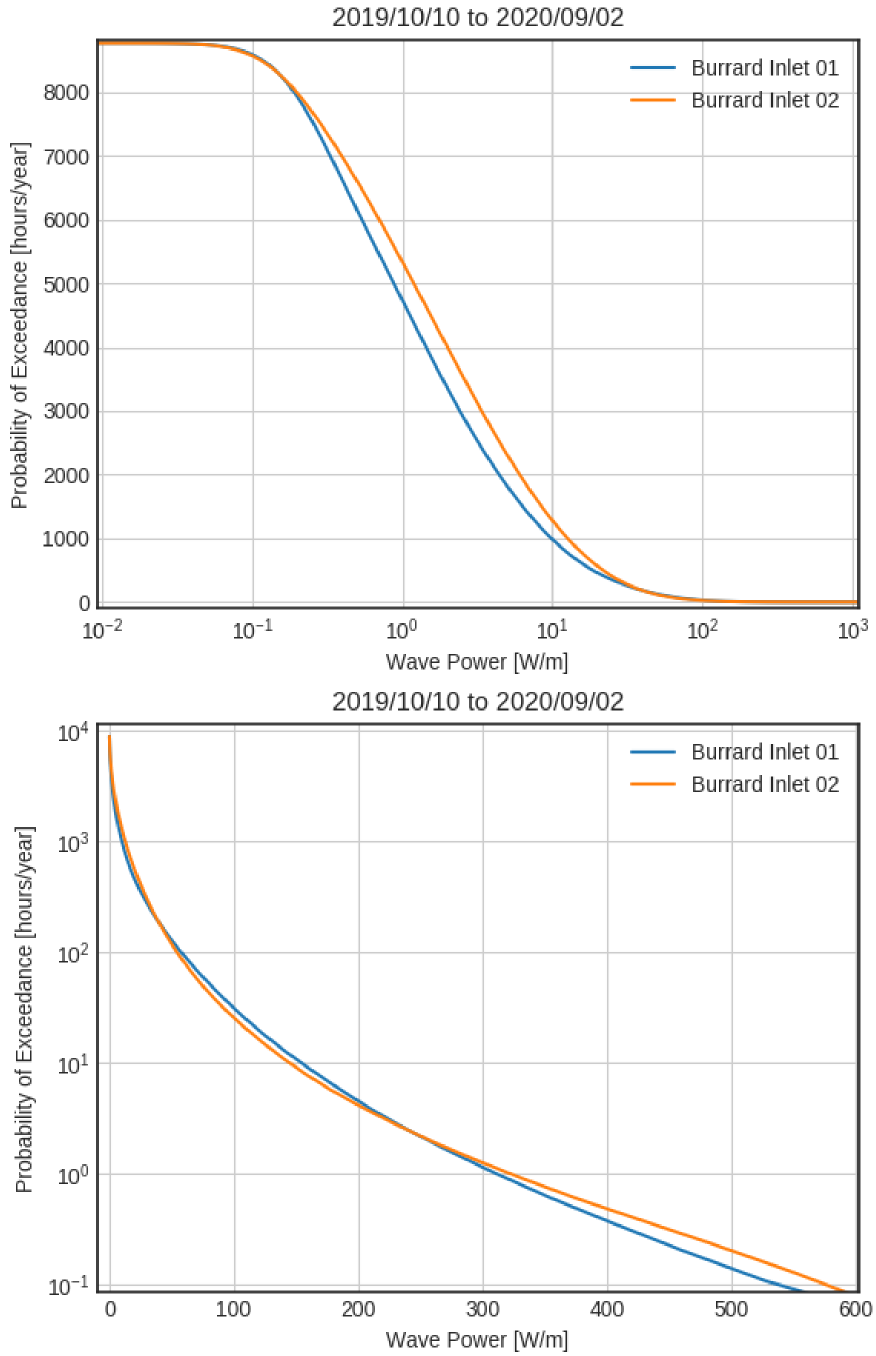


Figure 6: Wave power probability of exceedance for Burrard 1 and 2 buoys. Top: wave power axis is logarithmic. Bottom: probability of exceedance axis is logarithmic

3.3 Power Exceedance Probability due to Wakes

The automatic wake detection algorithm introduced in Section 2.4.1 produces a list of time intervals for wake activity. Wave power time series data that falls within these intervals is flagged as wake data. The remaining datapoints are attributed to wind and background noise.

The wave power time series data and associated wake event flags are combined to form a joint probability distribution, which provides the probability of a given data point meeting two requirements:

a) The wave power level for the data point exceeds a given threshold
b) The data point is flagged as a wake event

The probability distribution of wave power due to wakes is calculated by counting the number of datapoints where wave power exceeds a given threshold **and** the datapoint is flagged as a wake. Similarly, the probability distribution of wave power due to wind and background noise is found by calculating the number of datapoints where wave power exceeds a given threshold **and is not** flagged as a wake. The resulting probability distributions for both Burrard 1 and 2 buoys are plotted as solid lines in Figure 8 and Figure 9 respectively.

In Section 2.4.2, it was observed that the majority of errors in the automated wake detection algorithm are due to missed wake events. Therefore, the probability distributions calculated using the start and end times of the automatically detected wakes can be regarded as a lower bound to the true probability distributions. Upper bounds for the probability distributions were estimated using the results of the manual wake detection process discussed in Section 2.4.2. Using Burrard 2 data from 2020/03/27 to 2020/03/30, two wake power probability of exceedance distributions were produced: one using the start and end times of automatically detected wakes, the other using start and end times of the manually detected wakes. The resulting distributions are displayed in Figure 7, and as expected the distribution using manually detected wake intervals provides an upper bound to the automatically detected wake distribution.

The error between the manually and automatically detected wake power exceedance distributions is used to create the dashed curves in Figure 8 and Figure 9. The error is **added** to the solid orange curve to produce an upper bound for wave power exceedance due to wakes (dashed orange), while the error is **subtracted** from the solid blue curve to produce a lower bound for wave power exceedance due to wind/background noise (dashed blue). The error bounds for the wake power exceedance distributions illustrate that the automatic wake detection algorithm has the most difficulty detecting wakes when their power is low, as it is difficult to distinguish them from the background wind waves.

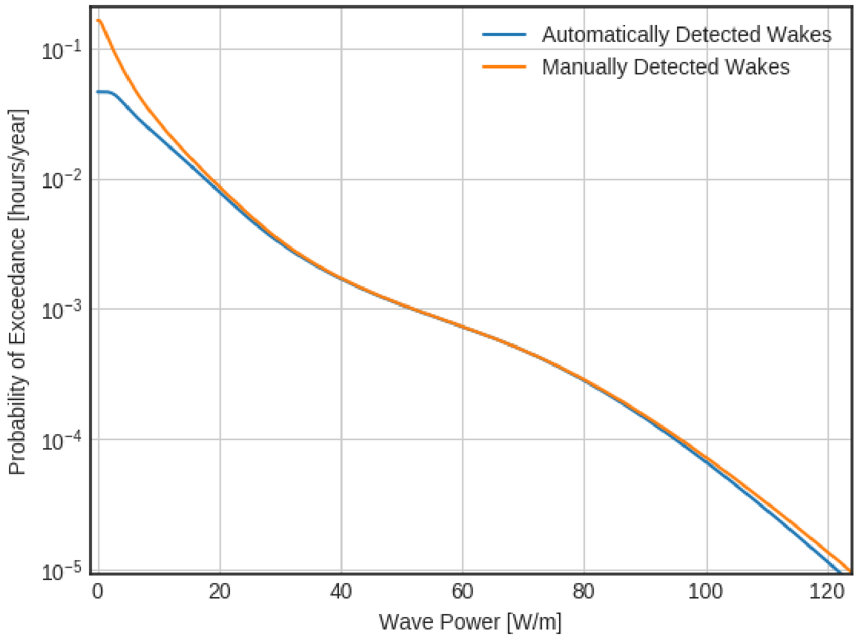


Figure 7: Wave power probability of exceedance distributions using the time intervals of automatically and manually detected wake events.

In Figure 8 and Figure 9, probability of exceedance curves for the total wave climate (including both wakes and wind/background noise) are plotted in black. Note that these are the same functions originally presented in Figure 6. However, because the y-scale is logarithmic in Figure 8 and Figure 9 it is difficult to quantify the fraction of the total probability distribution that is attributed to wake activity. This is resolved with Figure 10 which illustrates the percentages of the total probability of exceedance curves that are attributed to wakes for three power levels: 50 W/m, 100 W/m and 200 W/m.

The results in Figure 10 for Burrard 1 indicate that although high wave power levels are more likely to be caused by wind generated waves, wake activity notably increases the overall probability that wave power will exceed a given threshold. For example, wakes increase the probability of wave power exceeding 100 W/m at Burrard 1 by almost 1.2x. Wakes have a much larger impact at Burrard 2. For example, the probability of wave power exceeding 100 W/m is increased by over 2.3x due to wakes. Table 3: Increase in the overall probability of wave power exceeding various power levels due to wakes provides a summary of the increase in wave power exceedance probability due to wakes using the results from Figure 10.

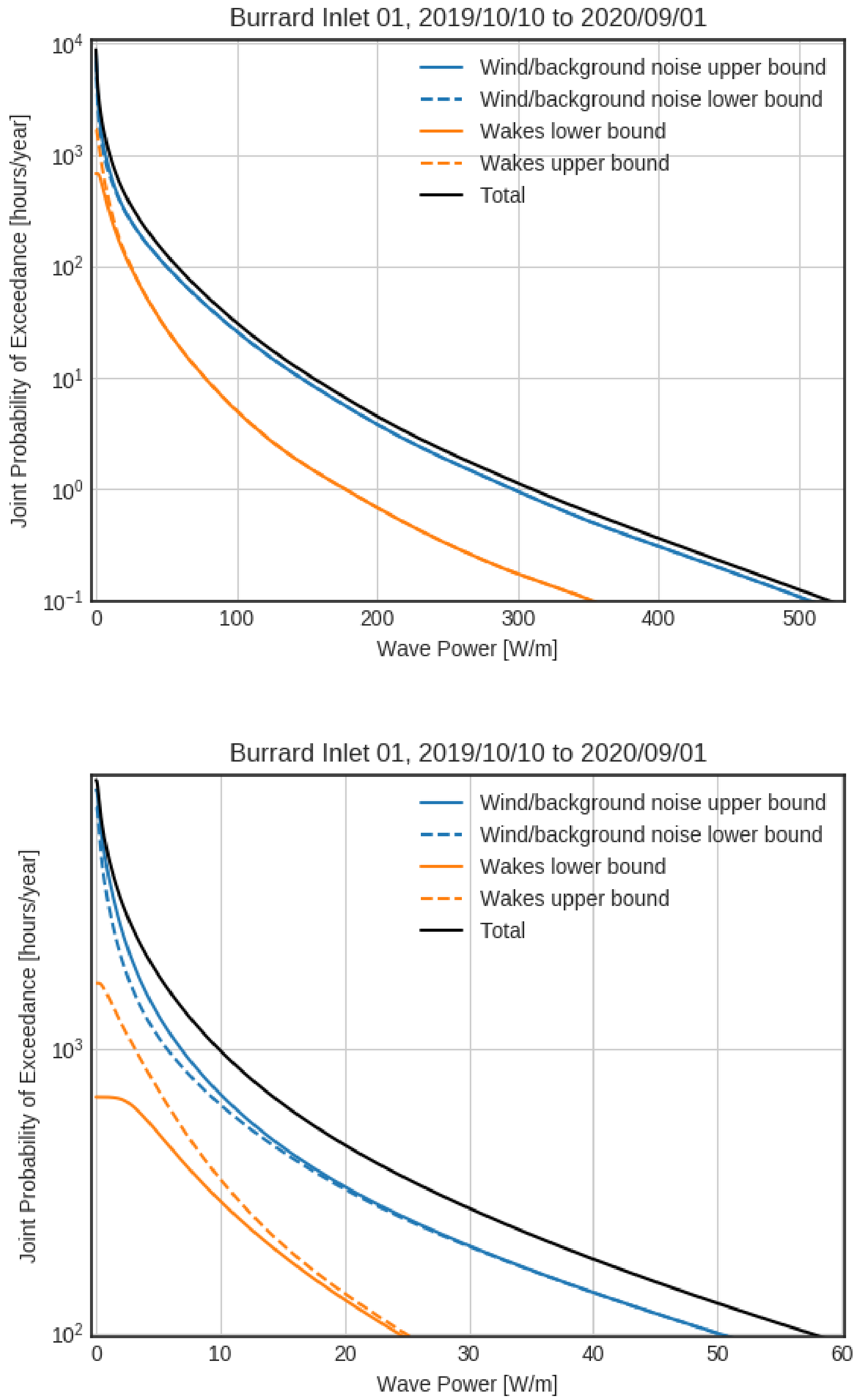


Figure 8: Burrard 1 probability of exceedance distributions for wakes and wind/background noise. The wake upper bound and wind/background noise lower bound are estimated from the automatic wake detection uncertainty analysis. The total probability distribution for all waves is also included. Top: full range of distributions. Bottom: zoomed to illustrate the uncertainty bounds at low power levels.

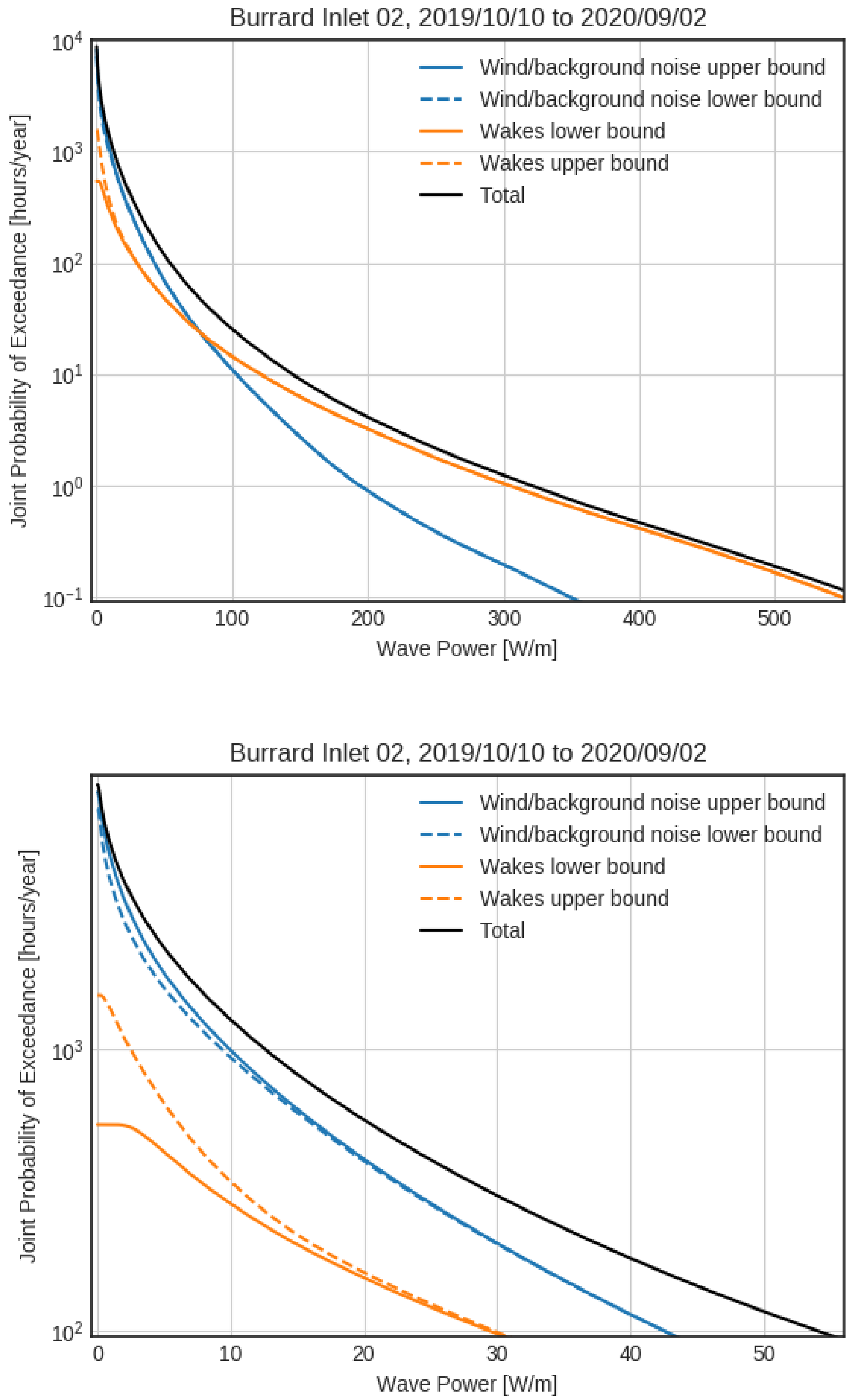


Figure 9: Burrard 2 probability of exceedance distributions for wakes and wind/background noise. The wake upper bound and wind/background noise lower bound are estimated from the automatic wake detection uncertainty analysis. The total probability distribution for all waves is also included. Top: full range of distributions. Bottom: zoomed to illustrate the uncertainty bounds at low power levels.

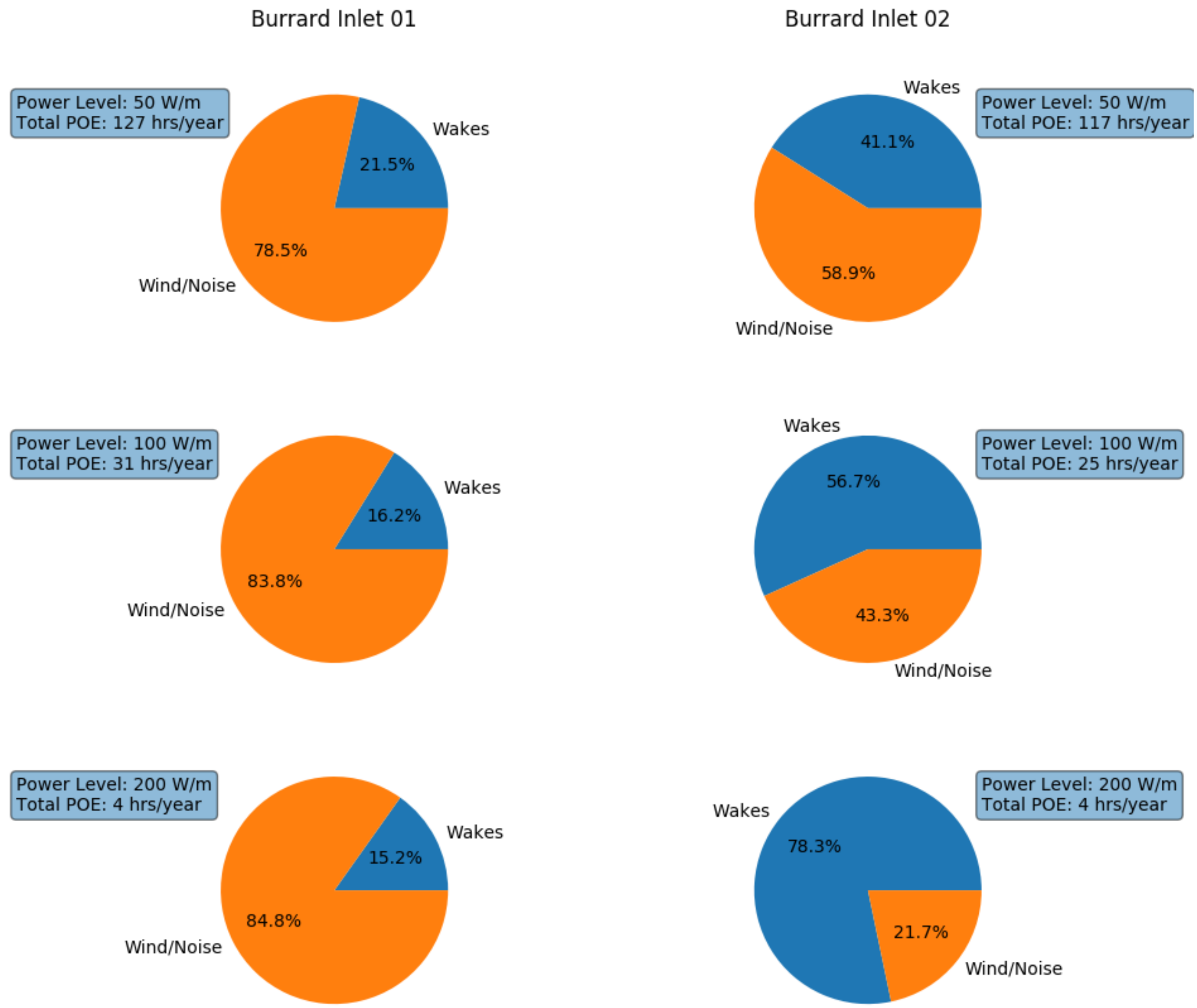


Figure 10: Fractions of the total probability of exceedance distributions for Burrard 1 and 2 that are attributed to wakes and wind/background noise. The three power levels for which the probabilities of exceedance are calculated are 50, 100 and 200 W/m.

Table 3: Increase in the overall probability of wave power exceeding various power levels due to wakes

Power Level	Burrard 1	Burrard 2
50 W/m	1.27	1.70
100 W/m	1.19	2.31
200 W/m	1.18	4.61

3.4 AIS Wake Link

Each detected wake event was linked to an AIS vessel type using the linking method described in Section 2.6. The number of wake events per vessel type per month are summarized in Table 4 for Burrard 1 and in Table 5 for Burrard 2. Most wake events were not linked to nearby AIS vessels, and these wakes are assumed to be produced by recreational traffic, as most recreational vessels do not have AIS connectivity.

Table 4: Monthly wake occurrences per AIS vessel type for Burrard 1

	Oct 2019	Nov 2019	Dec 2019	Jan 2020	Feb 2020	Mar 2020	Apr 2020	May 2020	Jun 2020	Jul 2020	Aug 2020
Minutes of Data	23040	32400	33255	33345	27945	28665	32400	33345	31995	33435	33480
No AIS	406	554	566	441	519	543	1028	822	1030	1187	1187
Tanker	2	8	13	1	6	7	1	10	9	2	10
Cargo	1	3	3	1	5	3	3	3	9	11	3
Pleasure Craft	11	20	12	17	17	6	2	37	71	54	83
Tug	145	202	280	158	230	179	60	308	349	383	373
Passenger	67	121	96	101	145	82	30	171	63	83	152
Fishing	1	0	0	0	1	0	0	6	10	1	0
Search and Rescue	4	11	8	2	8	4	0	17	36	24	27
Special Craft	24	33	47	21	41	26	9	35	54	47	69
Sailing Vessel	1	4	0	1	0	0	0	1	2	4	6
Other	1	2	2	2	6	1	0	0	2	1	2
TOTAL	**663**	**958**	**1027**	**745**	**978**	**851**	**1133**	**1410**	**1635**	**1797**	**1912**

Table 5: Monthly wake occurrences per AIS vessel type for Burrard 2

	Oct 2019	Nov 2019	Dec 2019	Jan 2020	Feb 2020	Mar 2020	Apr 2020	May 2020	Jun 2020	Jul 2020	Aug 2020
Minutes of Data	23085	32400	33300	33390	24570	28665	32355	33435	26235	30825	33390
No AIS	709	814	616	430	659	798	1351	1484	1268	1864	2005
Tanker	0	0	1	2	2	1	0	3	0	1	1
Cargo	1	3	2	4	4	0	0	0	0	1	0
Pleasure Craft	21	23	10	12	17	28	2	37	36	64	82
Tug	89	149	164	87	106	124	21	120	83	135	166
Passenger	5	16	29	15	24	15	4	34	7	12	19
Fishing	2	0	0	0	0	1	0	1	4	11	2

Search and Rescue	0	7	8	2	2	3	0	4	10	18	9
Special Craft	25	17	13	11	14	5	3	8	19	28	19
Sailing Vessel	1	1	0	0	0	0	0	3	6	0	2
Other	0	1	1	3	1	1	0	1	0	1	1
TOTAL	**853**	**1031**	**844**	**566**	**829**	**976**	**1381**	**1695**	**1433**	**2135**	**2306**

The seasonal variability of wake events is illustrated by the histograms of wake occurrences for Burrard 1 and 2 in Figure 11. Wave activity is represented as the number of wake occurrences per day to account for the varying number of minutes of data each month.

Observing Figure 11, it is notable that both locations experience more frequent wake activity during summer months than in winter. In general, Burrard 2 experienced more wake activity than Burrard 1. Most wakes at Burrard 2 were due to wake events not linked to AIS vessels. Even for Burrard 1 most wakes were not linked to AIS vessels, however a significant portion of wakes were linked to tugs and passenger vessels.

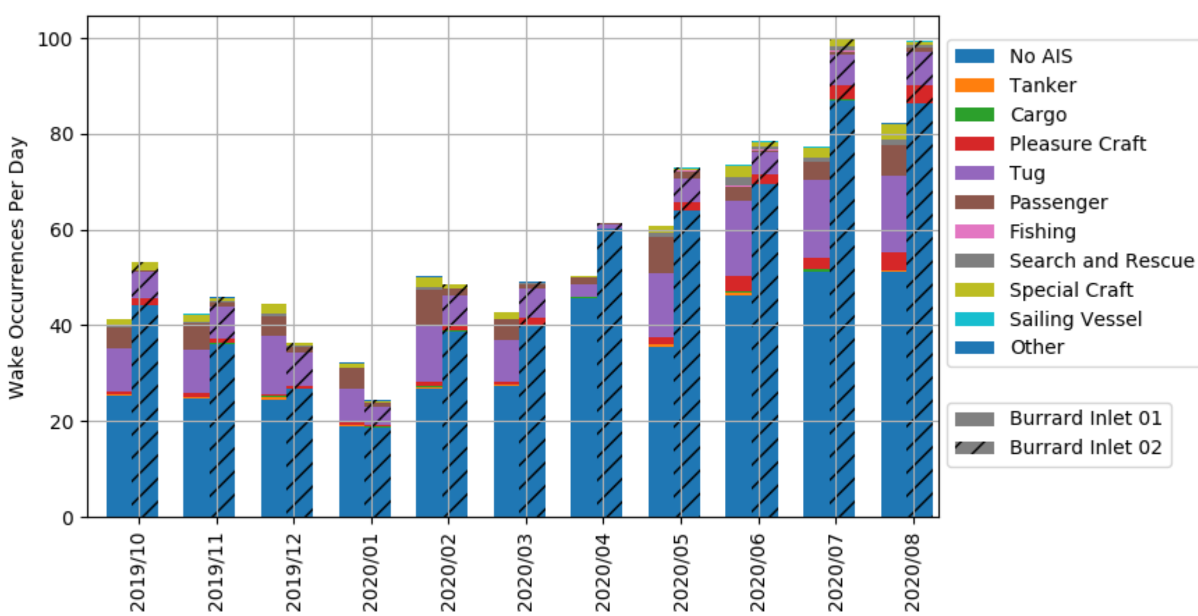


Figure 11: Wake occurrence histograms for Burrard 1 and 2

Wave power probability of exceedance distributions were produced for each AIS vessel type by counting the number of wave power time series datapoints that exceed a given power level **and** are flagged as a wake event belong to an AIS vessel of a given type. The resulting joint probability distributions are shown in Figure 12 and Figure 13 along with the wind/background noise power exceedance probability curves from Section 3.3 for reference.

Observing Figure 12 and Figure 13, it can be stated that, at both locations, high wave power levels are more often generated by vessels without AIS. At Burrard 1, the AIS vessels more often to produce high wave power levels are tugs, followed by passenger vessels and pleasure craft. At Burrard 2, the AIS vessels more often to produce high wave power levels are pleasure craft, followed by tugs and passenger vessels. At Burrard 2, wave power levels greater than approximately 100 W/m are more often produced by vessels without AIS.

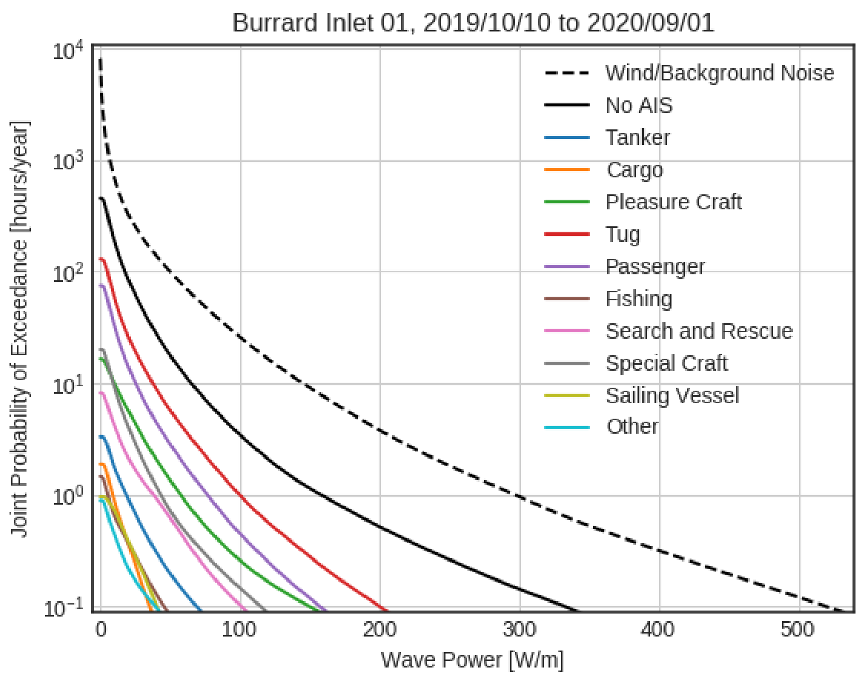


Figure 12: Burrard 1 wave power probability of exceedance distributions based on AIS vessel type.

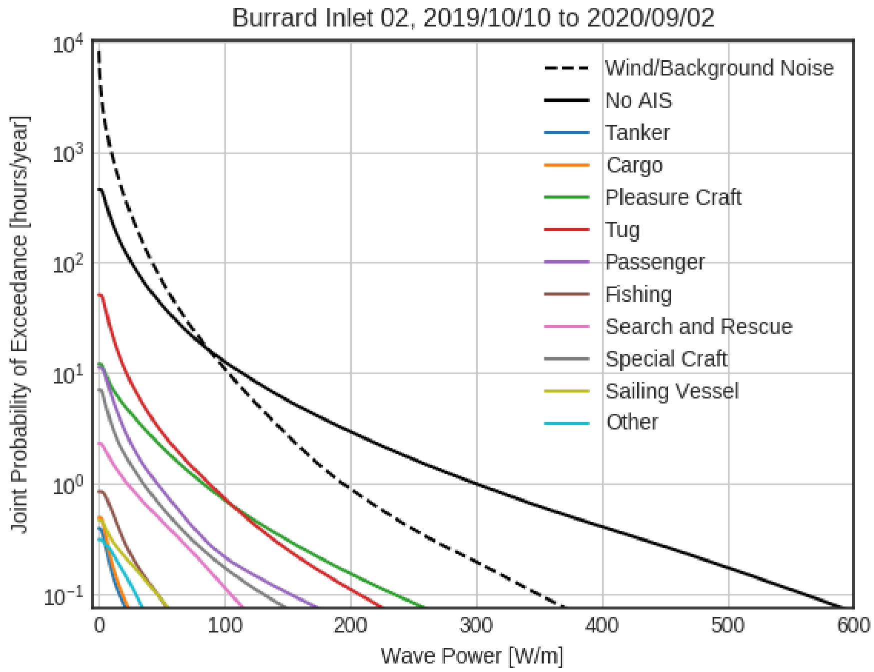


Figure 13: Burrard 2 wave power probability of exceedance distributions based on AIS vessel type.

The results in Figure 12 and Figure 13 indicate that vessels without AIS produce the greatest wave power exceedance probabilities, however this is largely because wake events from these vessels are significantly more frequent that other vessel types.

To better observe the wave power probability of exceedance distributions on a per vessel basis, the joint probability distributions in Figure 12 and Figure 13 are converted to ***conditional probability distributions***, which show the probability of wave power exceeding a given threshold provided a wake event is generated by an AIS vessel of a given class. These distributions are obtained by counting the number of wave power time series datapoints that exceed a given power level, but only using datapoints that are flagged as a wake event belonging to a given AIS vessel class. A benefit of conditional distributions over the joint probability distributions in Figure 12 and Figure 13 is that they are characterized by the vessel size, speed and distance from the buoy, rather than the frequency in which these wakes are produced

The resulting conditional probability distributions are shown in Figure 14 and Figure 15. To clearly extract the magnitude of the distributions for each AIS vessel class, the wave power exceedance probabilities are also plotted as bar charts for wave power levels of 50 W/m (Figure 16), 100 W/m (Figure 17) and 200 W/m (Figure 18).

Note that the units for the conditional probability distributions are percentages. For example, the probability of wave power due to tankers at Burrard 1 exceeding 50 W/m is approximately 6%.

Therefore given 1 hour of wake data from tankers at Burrard 1, wave power is expected to exceed 50 W/m for approximately 3.6 minutes.

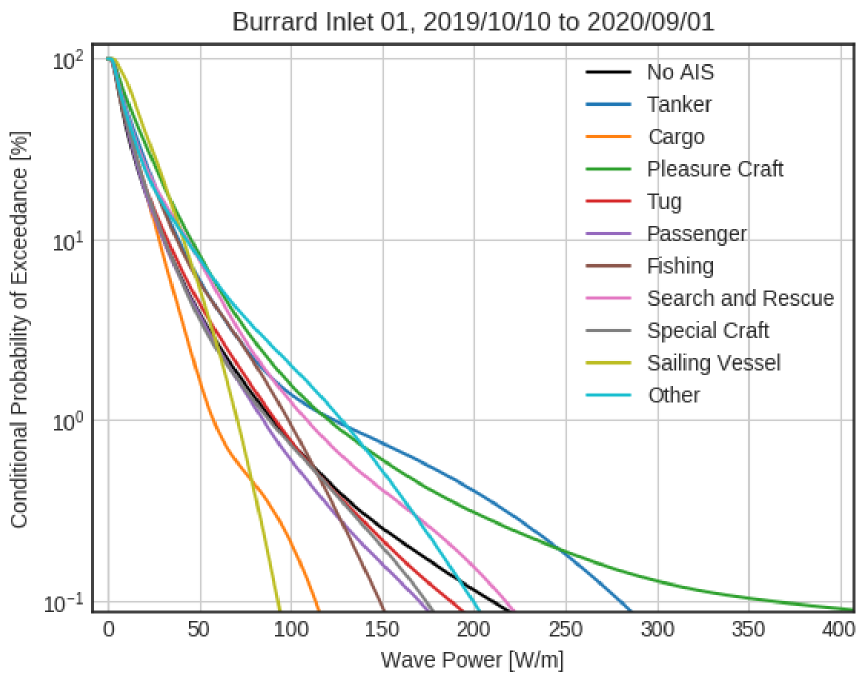


Figure 14: Burrard 1 conditional probability of exceedance distributions based on AIS vessel type.

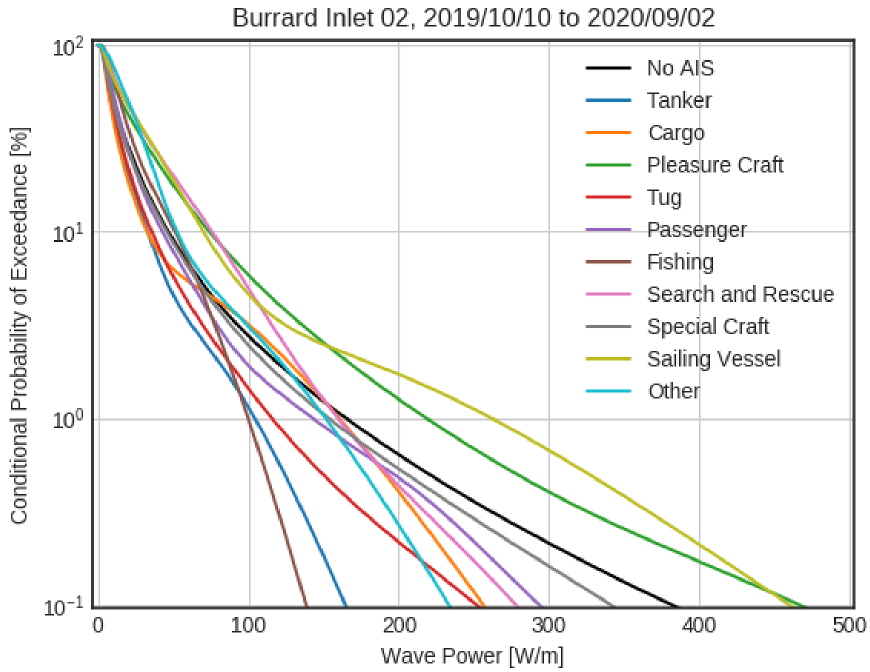


Figure 15: Burrard 1 conditional probability of exceedance distributions based on AIS vessel type.

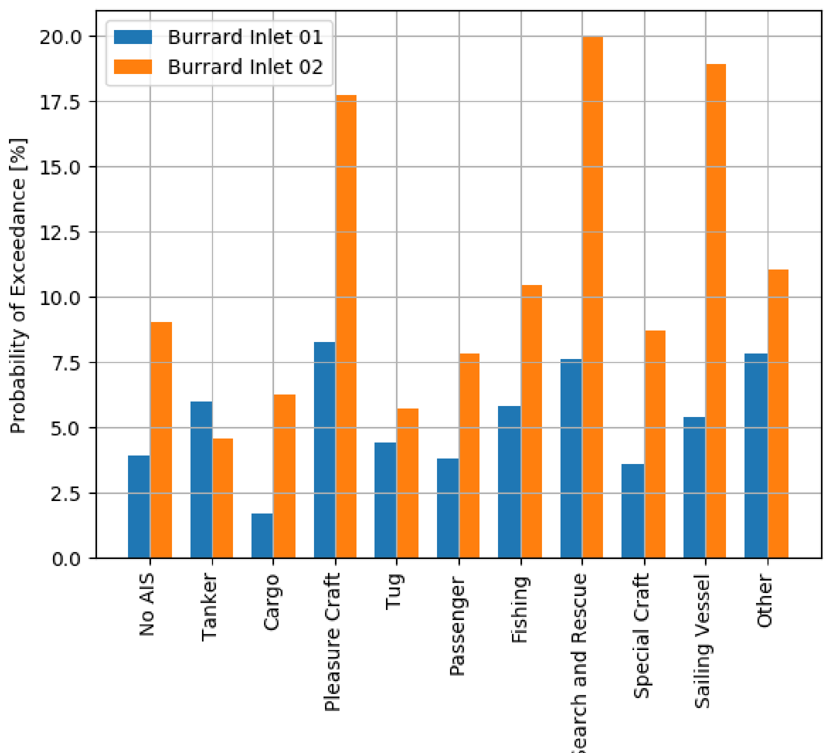


Figure 16: Conditional probability of wave power exceeding 50 W/m for vessel wakes at Burrard 1 and 2.

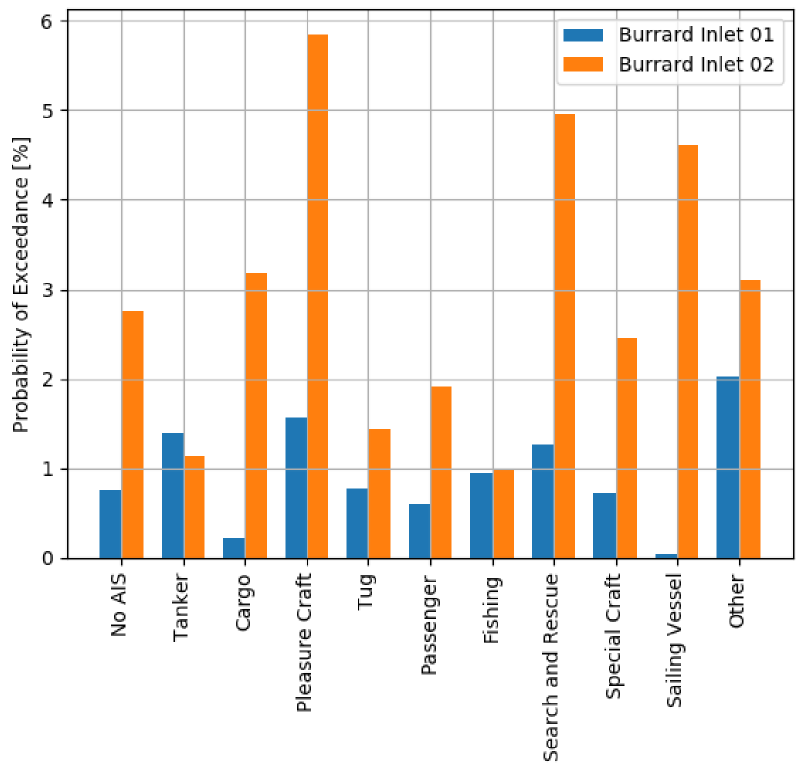


Figure 17: Conditional probability of wave power exceeding 100 W/m for vessel wakes at Burrard 1 and 2.

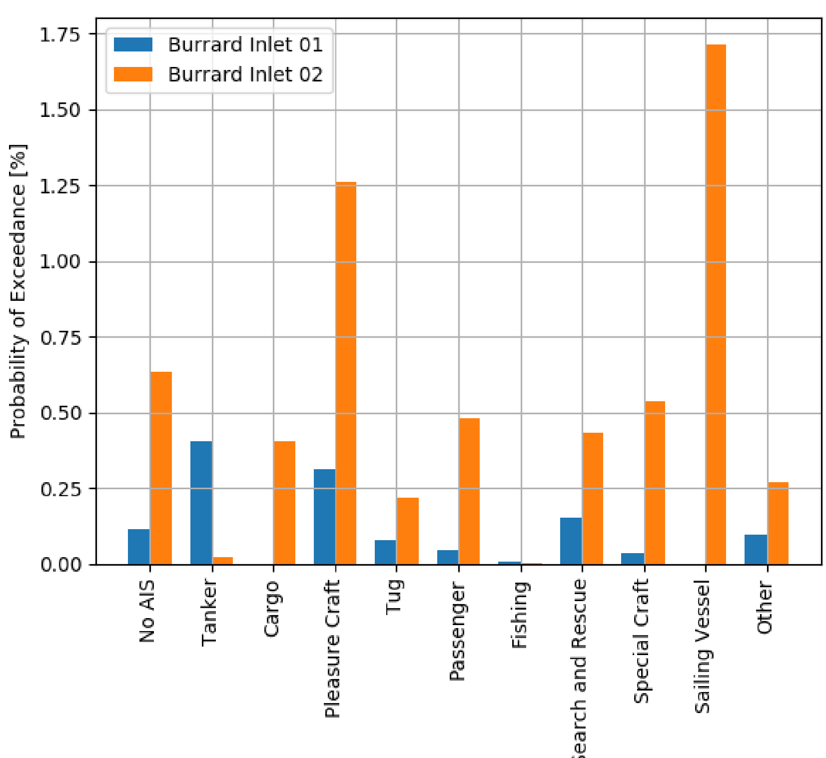


Figure 18: Conditional probability of wave power exceeding 200 W/m for vessel wakes at Burrard 1 and 2.

For all vessel types except tankers, the conditional probability of wave power exceedance due to wakes is greater at Burrard 2 than at Burrard 1. This is possibly because vessels travel at higher speeds and pass closer to the Burrard 2 location than Burrard 1. On a per wake basis, the probability of wave power exceeding 200 W/m is greatest for wakes from tankers and pleasure craft at Burrard 1, and is greatest for pleasure craft and sailing vessels at Burrard 2.

Conclusions

MarineLabs deployed and operated wave measurement buoys at two locations within Tsleil-Waututh Nation's traditional waters from Aug 2019 through to Sept 2020. The first location is offshore of TWN's main reserve in North Vancouver, and the second is located NE of Roche Point off Whey-ah-whichen/Cates Park. The buoys transmitted high resolution wave elevation timeseries so it could be processed to detect vessel wakes, link vessel wakes to AIS data, and provide statistics on the vessel wake activity with comparison to wind generated waves. Through the project, it was determined that vessel wakes can be successfully detected and linked with AIS data. The results indicate that at Burrard 1, high power levels arise more frequently from wind waves than vessel wake, yet vessel wakes increase the probability of wave power exceeding 100 W/m by a factor of 1.2. At Burrard 2, high power levels are more likely to arise from vessel wakes than wind waves, and power levels greater than 100W/m are more likely to be generated from vessel wakes than from wind waves by a factor of 4.6. Finally, it is found for both locations that vessels without AIS followed by Tugs and pleasure craft generate the highest wave power levels most frequently.

References

[1] L. H. Holthuijsen, *Waves in Oceanic and Coastal Waters*. Cambridge: Cambridge University Press, 2007.

[2] T. Torsvik, T. Soomere, I. Didenkulova, and A. Sheremet, “Identification of ship wake structures by a time-frequency method,” *J. Fluid Mech.*, vol. 765, pp. 229–251, 2015, doi: 10.1017/jfm.2014.734.

[3] S. W. Tan, “Predicting Boat-Generated Wave Heights: A Quantitative Analysis through Video Observations of Vessel Wakes.” 2012, [Online]. Available: https://www.lakeannavirginia.org/USNA_Wave_Height_Study_5_18_12.pdf.

[4] K. L. Huppert, J. T. Perron, and A. D. Ashton, “The influence of wave power on bedrock sea-cliff erosion in the Hawaiian islands,” *Geology*, vol. 48, no. 5, pp. 499–503, 2020, doi: 10.1130/G47113.1.