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Cowichan Lake Shoreline Assessment

Cowichan Lake Wave Energy Assessment

Final Report
May 27, 2022
KWL Project No. 2212.078

COWICHAN RIVER WATER SUPPLY

Prepared for:
Cowichan Valley Regional District

CVRD

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Executive Summary

Kerr Wood Leidal Associates Ltd. (KWL) was retained by the Cowichan Valley Regional District (CVRD) to complete a shoreline assessment of Cowichan Lake to determine the potential impacts of raising Cowichan Lake Weir. As part of the shoreline assessment, a wave energy analysis was performed to determine waves conditions on the lake shoreline and how they may change as a result of raising the weir.

A high-resolution spectral model was developed to estimate wave conditions based on the driving winds. The inputs to the model included wind conditions, lake bathymetry data, and water levels. To get the best spatial and temporal coverage, wind data from computational weather models was used, rather than historical wind data from local weather stations. The wind and wave model, were verified to observations collected by weather buoys, installed in the South Arm and south of Sa-Seen-Os Point from January 2021 to September 2021.

The wave modelling results indicate spatial and seasonal variation in wave height and energy. The South Arm of Cowichan Lake was observed to have low wave energy compared to the rest of the lake, as it is more enclosed and sheltered from the wind. Modelled wave energy was highest in the large open sections of the lake, northwest of Youbou. The largest wind speeds and wave heights occurred during the winter and fall; this is due to high winds generated by large-scale weather systems, which are more common in the winter. The wind speeds and wave heights were smaller in the summer, but winds were much more frequent, due to local sea-breezes, which are the prevailing source of wind in the summer.

In the summer months, boat wake also contributes to wave energy. The analysis evaluated the portion of wave energy generated by boat wakes using data obtained from the monitoring buoys. It was found that the wave energy due to boat wakes is minor, representing less than 5% of the total wave energy over the period of available buoy data, indicating that wind waves dominate the wave climate.

To evaluate wave conditions along the Cowichan Lake shoreline, the perimeter of the lake was divided into reaches, approximately 50 m long; a transect, running perpendicular to the shore, was generated within each reach. The model then computed results for incremental points along each transect. The wave conditions at the point along each transect closest to the shore, but before the wave breaks, was selected to represent incident shoreline conditions.

The work described in this memo has generated a statistically robust description of wave conditions along the Cowichan Lake shoreline. This description of wave conditions is used as an input to a subsequent task to develop a relationship between water level, wave energy, and the elevation of the natural boundary. The wave hind-cast will then be re-evaluated using water level boundary conditions which are consistent with the operation of the proposed weir. The re-computed wave and water level conditions will then be used to estimate the potential change in the natural boundary.

1. Introduction

Cowichan Valley Regional District (CVRD) retained Kerr Wood Leidal Associates Ltd. (KWL) to undertake a shoreline assessment for Cowichan Lake as part of the Cowichan River Water Supply Project. The objective of the shoreline assessment is to better understand potential shoreline impacts of the proposed raising of the Cowichan Lake weir to increase storage. A series of Technical Memoranda and Reports were prepared throughout the study and are included as appendices as follows:

- Appendix A: Project Approach and Methodology (KWL Technical Memorandum)
- Appendix B: Mapping, Field Work, Shoreline Characterization (KWL Technical Memorandum)
- Appendix C: 2020 Present Natural Boundary (Bazett Land Surveying Technical Memorandum)
- Appendix D: Cowichan Lake Inflow and Water Level Analysis (KWL Report)
- **Appendix E: Cowichan Lake Wave Energy Assessment (KWL Report)**
- Appendix F: Change in Natural Boundary (KWL Report)
- Appendix G: Property Impacts (KWL Report)

The purpose of this report, *Cowichan Lake Wave Energy Assessment*, is to summarize the work done to generate a statistically robust description of wave conditions along the Cowichan Lake shoreline. This description of wave conditions feeds into further analysis, summarized in Appendix F: *Change in Natural Boundary Change*, which examines the relationship between water level, wave energy, and the elevation of the natural boundary.

2. Method

Cowichan Lake is the largest lake on Southern Vancouver Island, with a length of about 32 km, a maximum width of 4 km, and a maximum depth of about 160 m. The Villages of Lake Cowichan, Youbou, and Honeymoon Bay are situated on the Lake's shore. However, much of the Lakeshore, especially to the northwest, is bordered by forest lands and is currently undeveloped. Cowichan Lake is at the head of the Cowichan Valley. The Lake is surrounded by mountainous forested terrain, except to the southeast along which runs the axis of the Cowichan Valley.

This project requires a statistically robust description of wave conditions along the entire Cowichan Lake shoreline. The standard approach for this type of task is to use a computational wave model to *hind-cast* wave conditions over a long historical period. For this project, a high-resolution spectral wave model was developed using the SWAN wave modelling software (TU Delft, 2021). A high-resolution digital elevation model was constructed to provide the bathymetric boundary condition. The model was forced with wind fields downscaled from archived forecasts of Environment and Climate Change Canada's (ECCC) High Resolution Deterministic Prediction System (HRDPS). Water levels were sourced from observations at the Cowichan Lake Weir. The model was run for the period of June 2017 to May 2021 inclusive.

3. Datum

The elevations reported in much of this study are presented in Canadian Geodetic Vertical Datum 2013 (CGVD2013). Much of the previous Cowichan Lake work references the CGVD28 datum (adopted in 1935). There is a difference of about 20 cm between these two reference datums at Cowichan Lake. The difference is not constant and ranges from 0.197 m at the east end of the lake to 0.218 m at the northwest end. At Cowichan Lake, the CGVD2013a datum is below CGVD28 datum, or in other words, the elevation of a common point, expressed with reference to CGVD2013a is higher than if expressed with reference to CGVD28.

A topographic survey of the existing weir crest was carried out as part of the detailed design of the weir upgrades. The survey indicates that it was constructed about 0.08 m higher than the original design elevation of the weir crest at 162.37 m CGVD28. The surveyed elevation of the existing weir crest used for this study is 162.45 m (CGVD28) or 162.65 (CGVD2013a).

Some of the discussion in this memo references the local Water Survey of Canada datum (WSCD) for the Cowichan Lake water level gauge (WSC, 2021). Like the chart datum, this datum is zero at approximately historic extreme low lake level. Using a datum referenced to water level simplifies the discussion of wave model development and the impact of bathymetric variations on wave conditions. The difference between CGVD2013 and WSCD is 161.944 m, i.e.:

$$WSCD = CGVD2013 - 161.144\ m$$

4. Wave Hind-Cast Development

This section describes the development of a wave hind-cast for Cowichan Lake. The hind-cast uses the SWAN wave spectral wave modelling software to estimate wave conditions based on the driving winds. Inputs to the model include an unstructured computational grid, a digital elevation model (DEM), water level, and wind conditions. Local measurements of wind and waves are used to evaluate the model inputs and outputs.

4.1 Data Collection

Bathymetric and Topographic Data

Multiple topographic and bathymetric datasets were used to create a comprehensive representation of Cowichan Lake's bathymetry and surrounding ground surface. Data sources include topographic data collected via light detection and ranging (LiDAR) and bathymetric data collected through multi-beam and single-beam boat surveys. Table 4-1 lists the topographic and bathymetric data sources used in this study.

Table 4-1: List of Topographic and Bathymetric Data Sources

Product	Data Type	Source*	Year	Vertical Datum	Horizontal Datum, Projection	Data Resolution
LiDAR	Point Cloud	(GeoBC) Quantum Spatial Canada	2019	CGVD2013	NAD83 (CSRS), UTM Zone 10N	Avg. Point Spacing 0.2 m
LiDAR	Point Cloud	(CVRD) Terra Remote Sensing Inc.	2008	CGVD28	NAD83, UTM Zone 10N	Avg. Point Spacing 0.4 m
Multibeam Survey	Point Grid	(CVRD) Canadian Hydrographic Service	2013	CGVD28	NAD83, UTM Zone 10N	Avg. Point Spacing 2 m
Single Beam Survey	Point Track	Bazett Land Surveying Inc.	2020	CGVD2013	NAD83, UTM Zone 10N	Varies
Single Beam Survey	Point Track	(CVRD) Terra Remote Sensing Inc.	2012	CGVD28	NAD83, UTM Zone 10N	Varies
*The institution in brackets indicates, where applicable, the third-party from which the source data was obtained						

With the available LiDAR and multibeam bathymetric surveys, there is good data resolution and coverage on land, as well as in deeper areas of the lake (generally below -5 m). However, in shallower areas of the lake - such as bays and the general nearshore – data is limited to select areas and is collected in a linear fashion along boat tracks.

Historic Wind Data

Limited wind measurements are available in the vicinity of Cowichan Lake. There is a weather station operated by the Ministry of Forest, Lands and Natural Resource Operation (MFLNRO) at Mesachie Lake. The data from this station was obtained through the PCIC Data Portal. This station appears to be malfunctioning as most of the records since the start of 2021 appear invalid. There is another weather station at Palsson Elementary School (in the Village of Lake Cowichan), operated by the Vancouver Island School-Based Weather Station Network. The completeness of this record and the data quality appears to be acceptable. However, the anemometer is installed on a short mast on a flat-topped roof, and further, the site also borders a large, forested area. These factors will impact the local wind speed and direction. The closest Environment and Climate Change Canada (ECCC) Weather Station is at North Cowichan. While not directly representative of the conditions at Cowichan Lake, this station was used as a benchmark for evaluating inter-annual variability of wind conditions. Table 4-2 below provides the details on the location and data availability for each of the historic datasets.

Table 4-2: Location and Data Availability for each Historic Weather Dataset

Station Name	Network	Lat	Lon	Elev (m)
Palsson Elementary	VISBWSN	48.829	-124.052	172
MESACHIE 2	FLNRO-WMB	48.8181	-124.1361	210
SUMMIT	FLNRO-WMB	48.9283	-124.6483	857
NORTH COWICHAN	ECCC	48.82	-123.72	44.8

Modelled Wind

Wind data from computational weather models are useful because, unlike weather stations, they typically have continuous spatial and temporal coverage. Two different model datasets were evaluated in this work.

The first weather model used is the *High-Resolution Deterministic Prediction System* (HRDPS) from the ECCC. This is a forecast model run at 2.5 km resolution. Archived forecasts back to July 2017 are available through the Canadian Surface Prediction Archive[1].

The second model, which was used was the *Climate Forecast System Reanalysis* from NCEP. This reanalysis model has an approximate resolution of 38 km. The "version 2" re-analysis is available 2011 to present from the NCAR Research Data Archive[2]. The "version 1" reanalysis is available 1979 to 2010.

Historic Water Levels

Lake levels are continuously monitored at the Cowichan Lake weir by the Water Survey of Canada (WSC). For the purposes of this work, the full archive of daily lake levels was obtained. The levels are recorded in local WSC datum (WSCD).

Wave and Wind Data Collection

As part of this project, two small wave buoys were deployed in January of 2021 and were recovered in September 2021. These buoys, developed and operated by MarineLabs of Victoria, BC, measure both wave and wind conditions. Buoy 1 was located in the South Arm, mid-channel, near the "Cottage Collection" development (48.828N, -124.129E). Buoy 2 was located mid-channel south of Sa-Seen-Os Point, near Youbou (48.862N, -124.190E). The buoy locations are shown on the map in Figure 4-1.

[1] https://caspar-data.ca/
[2] https://rda.ucar.edu

Wind measurements from these buoys were essential as there are no other measurements available which are indicative of wind speed over water on the lake. However, the anemometer on the deployed buoys is at 0.76 m height above water level. This is far below the 10 m standard height for wind measurements. Because of the friction of the wind blowing over the earth's surface, wind measurements at a lower height will tend to be smaller in magnitude. However, the wind measurements may be scaled to standard height using an assumed wind profile shape and surface roughness, such as the log profile (DNV-GL, 2014).

The wave measurements are important for calibrating the wave model and evaluating the skill; this process is discussed in Appendix E-1 of this report. The buoy technology also allows the differentiation between wind and vessel wake. A report on the boat wake climate of the two buoys is provided in Appendix E-2; the results are summarized in Section 5.

Figure 4-1: Wave Buoy Deployments Locations

4.2 Digital Elevation Model (DEM)

The digital elevation model (DEM) of Cowichan Lake was built using Esri's ArcGIS Pro 2.8 "Topo to Raster" interpolation tool. The Topo to Raster tool, based on the ANUDEM program developed by Michael Hutchinson, is a modified spline interpolation method specifically designed for the creation of hydrologically correct DEMs[3]. Inputs to the tool are the topographic and bathymetric point data sources listed in Table 4-1. Where two or more datasets overlap in coverage, only the higher-resolution data is retained.

Before running Topo to Raster, vertical datum differences between the input data sources were reconciled. CGVD2013 was selected as the project datum; datasets referencing the older CGVD28 vertical datum were therefore shifted to CGVD2013. While the datum offset between CGVD28 and CGVD2013 varies from +0.197 m to +0.218 m across the Lake, the variation of 0.021 m was deemed insignificant, and a uniform offset value of +0.2 m was used to shift the elevations from CGVD28 to CGVD2013.

The output DEM is a raster surface with a grid cell size of 0.2 m. Horizontal and vertical data resolution has been effectively retained from data input to the resulting integrated DEM.

4.3 Shoreline Transects

The Cowichan Lake shoreline and its islands were discretized into along-shore "reaches" or stretches of shoreline which are approximately 50 m long, for a total of 2222 reaches. For each reach a cross-shore transect was generated based on the DEM. Generally, the transects spanned the area from -6 to 4.5 m elevation (WSCD), with points along the transect at increments of 0.25 m in the vertical.

Wave model results were computed at each point along every transect. Discretizing the shoreline in this way enables quantitative comparison of wave conditions with other shoreline variables such as sediment composition, and the natural boundary elevation.

4.4 Wind Field Downscaling

On detailed investigation, it was found that the HRDPS wind fields were insufficiently resolved to adequately represent wind conditions over the lake (See Appendix E-1 of this report). To address this problem the HRDPS wind fields were downscaled using the *WindNinja* wind modelling software[4]. The domain averaged winds from HRDPS were used to force the wind model, which solves the flow field based on conservation of mass and momentum. The resulting wind fields, approximately 100 m in resolution, show much greater spatial variability due to local topography, and importantly show much better agreement compared to the weather buoy wind measurements. See Appendix E-1 of this report for more details.

4.5 Wave Model Grid

The model uses an unstructured triangular grid. The shoreline was derived from the 4.5 m (WSCD) contour. The grid has a resolution of 5 m for areas higher than the -2 m contour and grows to 100 m in areas below the -25 m contour. Elevations were interpolated from the DEM onto the nodes of the unstructured grid.

[3] https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/topo-to-raster.htm
[4] https://weather.firelab.org/windninja/

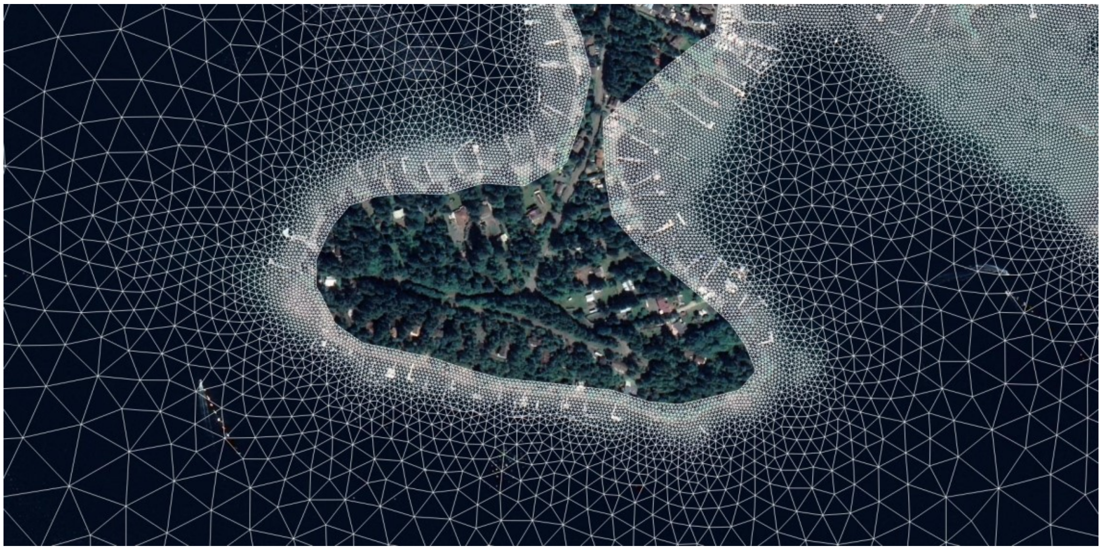

Figure 4-2: Wave Model Grid Around Sa-Seen-Os Point

4.6 Model Setup

The wave model was set up using the SWAN wave modelling software (41.31). The model was driven with wind fields (Section 4.3) and with spatially constant water levels (Section 4.1). The model was set up to run in stationary mode at one-hour time-steps throughout the hind-cast period of June 2017 to May 2021. The model was calibrated against measurements from the weather buoys, and model evaluation was carried out (see Appendix E-1 of this report).

5. Vessel Wake Measurements

The vessel wake climate at Cowichan Lake was investigated by MarineLabs, the operator of the wave buoys (see Appendix E-2 for details). As expected, the occurrences of boat wakes increased steadily from January until reaching a peak in July and August. During these peak months, the South Arm Buoy observed about 30 wakes per day, while the Sa-seen-Os Point Buoy observed about 12. Most wake events had a maximum wave height of less than 0.3 m. The largest recorded wake height was 0.65 m.

As part of this work, MarineLabs provided a record of the average total wave power, and the average wake wave power for each recording period. This record was used to calculate the portion of wave energy occurring due to boat wakes. Over the full observation record, about 4.4% of the total wave energy at the South Arm Buoy was due to wakes, and only about 0.7% at the Sa-seen-Os Point Buoy. This finding indicates that boat wakes currently play a secondary role to winds in determining the wave climate of Cowichan Lake.

6. Results and Discussion

Wave parameters were output at every grid node for each hour of the hind-cast during the model run. Figure 6-1 shows the cumulative wave energy over Cowichan Lake. As expected because of the limited fetch, the South Arm of the Lake has low wave energy compared to the rest of the Lake. Wave energy is high areas with larger fetch, in the northern portion of the lake (northwest of Youbou), where there is significant fetch from both the NW and SE.

The largest significant wave height in the hind-cast is about 0.6 m, which occurred around Youbou, Bald Mountain, and some areas of the north shore northwest of Youbou. Typical significant wave heights were small everywhere in the Lake with an average of less than 0.05 m.

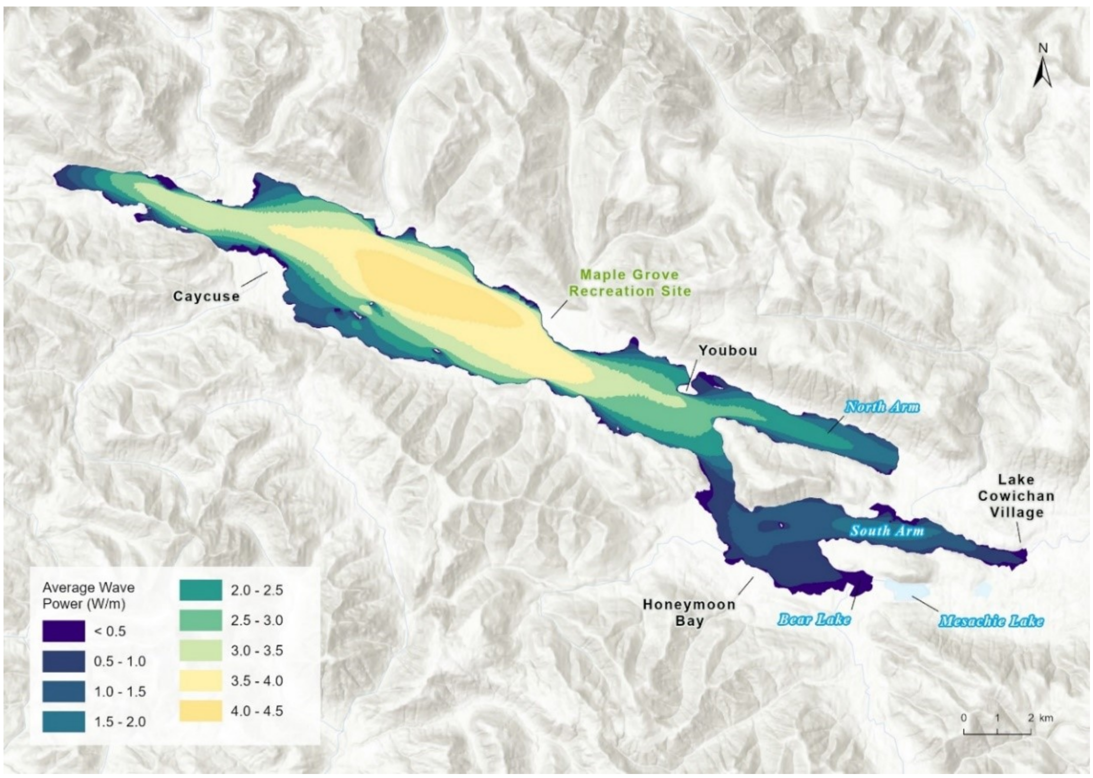

Figure 6-1: Cumulative Wave Energy [W-hr/m] Over the Hind-Cast Period

6.1 Wind and Wave Climate

Peak and mean wind speeds tend to be larger in the winter months compared to the summer. However, there are important differences in the characteristics of each season[5].

During winter, winds are driven primarily by large-scale weather systems propagating through the region. This season is characterized by frequent storms, with peak wind speeds up to about 15 m/s (55 km/h), wave heights up to about 0.6 m, and lasting up to several days. Lull periods between storms,

[5] For the purpose of this discussion, the seasons are Dec-Jan-Feb (winter), Mar-Apr-May (spring), Jun-Jul-Aug (summer) and Sept-Oct-Nov (fall).

where wind speeds are below 5 m/s (18 km/h) and waves are small, may last days to weeks. The direction of the largest wind speeds tends to align with the northwest and southeast axes of the of the lake. Winds blowing perpendicular to the axis of the lake tend to be lower in magnitude due to the sheltering effect of the surrounding mountains.

Through the spring, the frequency and magnitude of strong large-scale weather systems declines, and the influence of thermally driven *sea-breezes* increases. A *sea-breeze* occurs because of differential heating of the land and ocean by the sun during the daylight hours and occurs frequently over the Salish Sea on clear days (Thomson, 1981). On the east coast of Vancouver Island and Cowichan Lake, the sea breeze is from the easterly direction. The sea breeze typically peaks around 6 m/s, producing significant wave heights of up to about 0.25 m on Cowichan Lake. During the night a similar, but much weaker, *land breeze* occurs due to differential cooling of the land and ocean and flows from the westerly direction.

During the summer, strong large-scale weather systems are infrequent, so sea breeze tends to be the dominant driver of wind conditions. When the sea breeze is dominant, lull conditions typically last only the nighttime hours. In the summer the sea breeze is sometimes observed from the west, instead of the east and driven by thermal gradients between Vancouver Island and Pacific Ocean. Preliminary review of MFLNRO weather stations in the area suggests that this reversal of the sea breeze direction occurs due to strong inflow up the Nitinat Valley, which then outflows down the Cowichan Valley, similar to the *Qualicum Wind*. During these periods the night-time land-breeze also flows from the west, so that there is no reversal of wind direction day to night.

In the fall season, the occurrences of sea-breeze diminish, and wind conditions quickly transition to be dominated by large-scale weather systems, similar to the climate experienced through the winter months. However, on average, wind speeds are somewhat lower than in the winter months.

In general, the largest wind speeds and wave heights occur during storm activity in the fall and winter months. However, there are frequent lull periods between the storms. Peak wind speeds and wave heights are smaller during the spring and summer months but occur much more frequently and during the daylight hours due to the daily sea breeze.

Boat wakes are prevalent during the summer recreation season (July and August). Even during this peak period, the portion of wave energy coming from wakes is about 8% in the South Arm and about 2% at Sa-Seem-Os Point. Averaged over the period of available observations (January to September 2021), the portion of wake energy is even less, with about 4.4% in the South Arm, and about 0.7% at the Sa-seen-Os Point. The amount of wake wave energy on the lake is approximately proportional to the amount of boating activity (e.g., boat hours per month), but will also depend on other factors such as boat type and activity. Wave energy due to boat wakes adds to the energy due to winds, and together they define the total wave conditions on the lake. Currently the wave energy due to boat wakes is small compared to the prevailing wind-wave energy; however, any future changes in the frequency of boating activity will produce roughly proportional changes in the amount of wake wave energy on the lake. Future boating activity would have to be many times greater than current levels to create a wake environment with energy similar to the prevailing wind-wave environment.

6.2 Shoreline Wave Conditions

This work was aimed at characterizing waves at the shoreline, to enable assessment of potential changes in the natural boundary. As waves approach the shoreline, they typically lose energy density to a number of mechanisms, including refraction, diffraction, bottom friction, and breaking. For the natural boundary analysis, the shoreline incident wave energy before breaking was chosen to be the parameter of interest. This was evaluated using the shoreline transects discussed in Section 4.3. First, the parametric wave results were interpolated onto the shoreline transect nodes. Then, at each time step, the wave conditions along each transect node were evaluated sequentially. The wave conditions at the node closest to shore, but before depth induced wave breaking, were selected to represent the shoreline incident wave conditions. This results in a single time series of wave conditions for each transect throughout the hind-cast. Figure 6-2 shows the shoreline incident cumulative wave energy at each transect around the lake for the full four-year hind-cast.

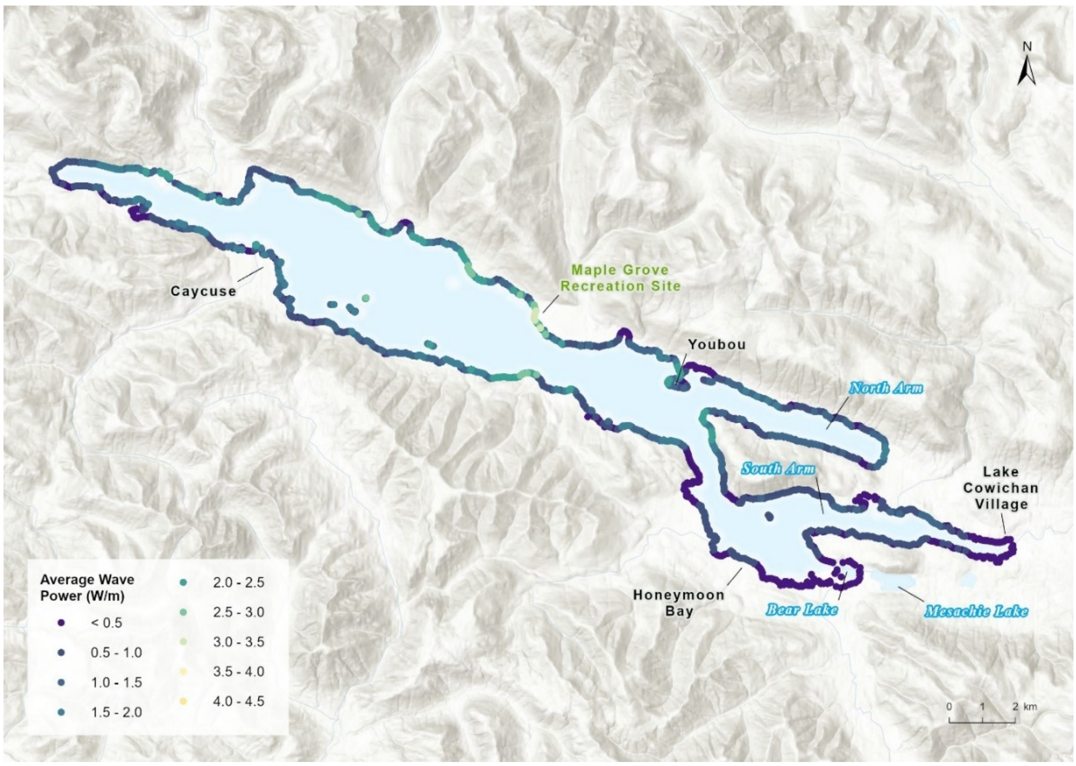

Figure 6-2: Cumulative Wave Energy [W-hr/m] Over the Hind-cast Period at Transect Locations.

7. Next Steps

The work described in this memo has generated a statistically robust description of wave conditions along the Cowichan Lake shoreline. This description of wave conditions is used as an input to a subsequent task to develop a relationship between water level, wave energy, and the elevation of the natural boundary. The wave hind-cast will then be re-evaluated using water level boundary conditions which are consistent with the operation of the proposed weir. The re-computed wave and water level conditions will then be used to estimate the potential change in the natural boundary. These tasks will be reported in *Appendix F: Change in Natural Boundary* of the *Cowichan Lake Shoreline Assessment.*

COWICHAN VALLEY REGIONAL DISTRICT
Cowichan Lake Shoreline Assessment
Cowichan Lake Wave Energy Assessment
Final Report
May 27, 2022

Submission

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Revision History

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0	May 27, 2022	FINAL		CEH

Proudly certified as a leader in quality management under Engineers and Geoscientists BC's OQM Program from 2013 to 2021.

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Appendix E-1

Wave Model Setup and Evaluation

Appendix E-1

Contents

Figures

Wave Model Forcing

The Cowichan Lake wave model developed for this project uses the SWAN spectral wave modelling software. Inputs to the model include an unstructured computational grid, a digital elevation model (DEM), water level, and wind conditions. This appendix provides more detail on the wind fields used to drive the model, and on evaluation of the model skill.

Initially the wave model was setup to be driven directly by the Environment and Climate Change Canada (ECCC) High Resolution Deterministic Prediction System (HRDPS) spatially and temporally variable winds. The HRDPS is a forecast model run every six hours, with output at hourly resolution. The first three (0-2) hours of each forecast are used to "spin-up" the model, to the point where it is making accurate estimates. To create a continuous hourly record of wind fields, the forecast hours three through seven of each forecast were concatenated together.

Upon investigation, it was found that the HRDPS wind fields tend to over-estimate wind speeds over Cowichan Lake when winds are blowing from directions other than E, and SE. This is confirmed by both the weather buoy measurements, but also the corresponding modelled wave heights and buoy measurements. The reason for this over-estimate appears to be that Cowichan Lake is surrounded by forested, mountainous terrain from the other directions. The HRDPS, even with a resolution of 2.5 km, has only a few grid points over many of these mountain features, and so is unable to resolve the details of the flow.

Downscaling Wind Fields

Model-based downscaling using the *WindNinja* wind modelling software[1] was used to better resolve the wind fields in the region over and around the Lake. This software is developed by the Missoula Fire Sciences Laboratory for the US Department of Agriculture and is primarily used to support wildfire management activities in wild, mountainous terrain.

WindNinja requires the DEM of the model region as an input. The automatic download feature within the software was used to acquire a 250m DEM of the region surrounding Cowichan Lake from the *Global Multi-resolution Terrain Elevation Data* DEM[2]. Because WindNinja does not include an option for spatially variable surface friction, the friction for the entire domain was set assuming tree cover, even the lake surface. The 'conservation of mass and momentum' solver was used, which runs a customized version of the Open-FOAM CFD software in the background. Domain vector-averaged wind velocities were used to drive the model. The model was run in a temporally stationary configuration for a range of domain average wind speeds, and directions. The temporal record was then recovered by interpolating the stationary results based on the domain average wind speed at each time step in the record.

This approach requires a record of domain average winds. Two sources were evaluated for the purpose. The first source was the HDRPS, which was vector averaged over the domain at each time step. The second was the CFSR, for which the closest grid point to Cowichan Lake was selected. It was found that the domain average wind velocity as derived from the HRDPS resulted in a much better representation of the wind conditions as measured by the weather buoys. However, there were some small gaps in the HRDPS which were filled using the CFSR data.

[1] https://weather.firelab.org/windninja/
[2] https://topotools.cr.usgs.gov/gmted_viewer/viewer.htm

Figure 1 and Figure 2 below show the HDRPS wind fields, with the HRDPS-WindNinja downscaled wind fields, and the wind station measurements including the buoys. The quivers originating from black dots at their roots are directly from HRDPS. The quivers originating from white dots are from the wind measurements stations. The quivers without dots at their root are from the downscaled wind fields, as interpolated based on the HRDPS domain average wind velocity.

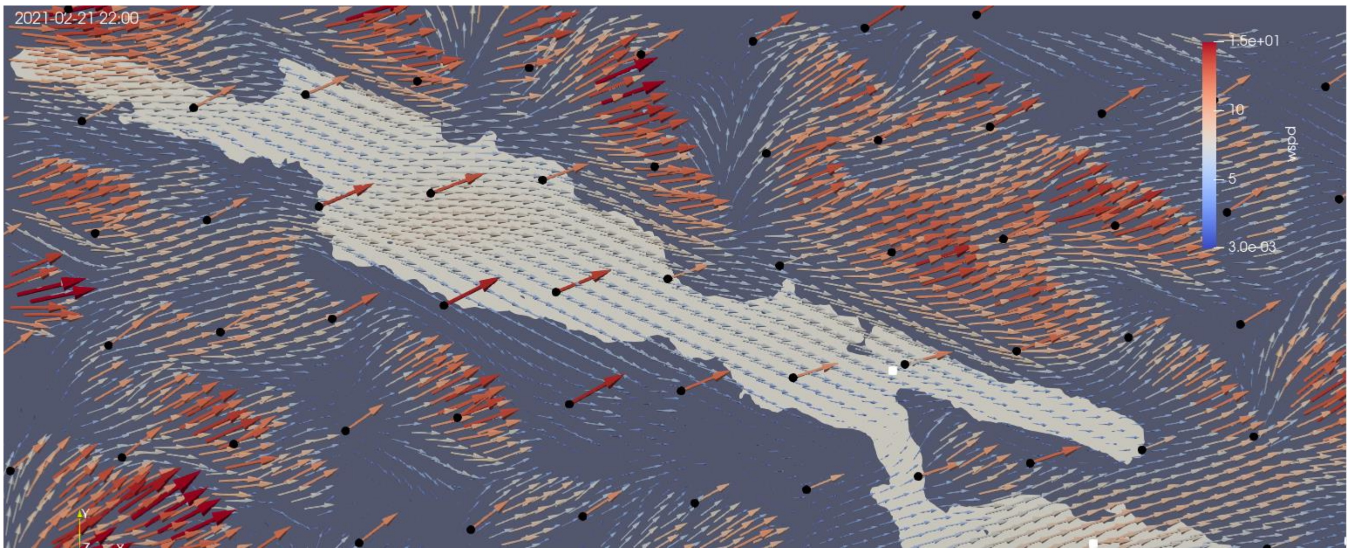

Figure 1: Wind Fields Over Cowichan Lake for 2021-02-21 22:00 (UTC)

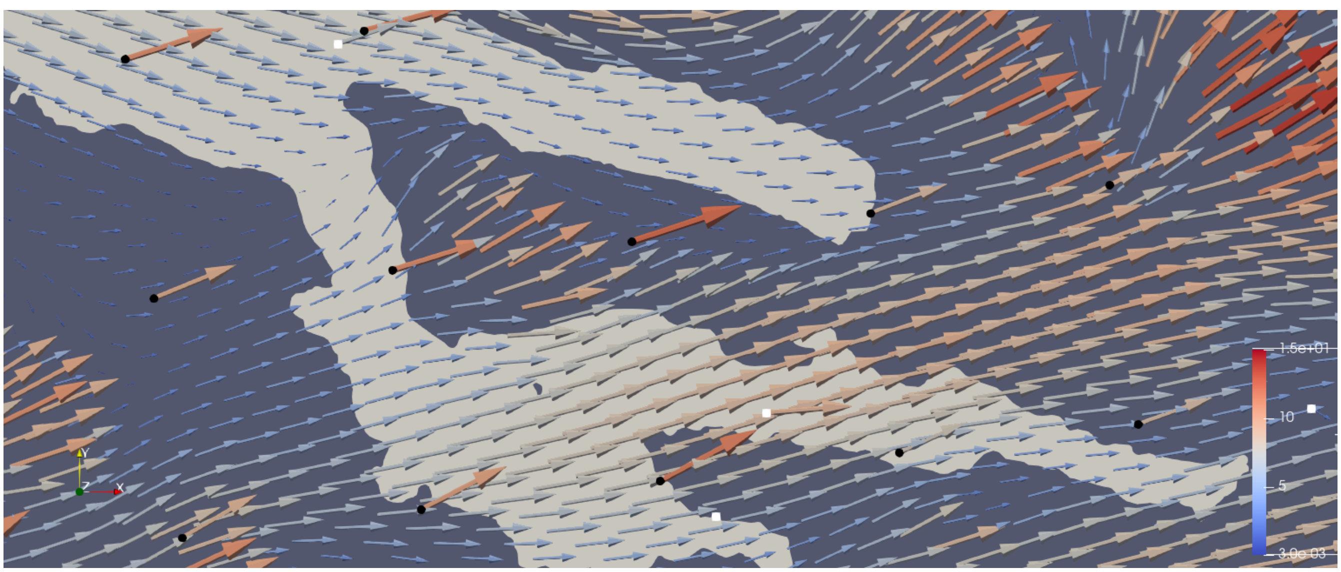

Figure 2: As in Figure 1, zoomed to the South End of Cowichan Lake.

There is considerably more variability in the downscaled wind fields due to the influence of local topography, which is not captured in the HRDPS model directly. The winds speeds tend to accelerate over mountain ridges and slow in the valleys and over the Lake.

Model Evaluation

Wind Model

For direct comparison of the measured and modelled winds, the winds measure at the buoys were scaled to 10 m using a log profile and a surface roughness of 0.01 m (DNV-GL, 2014). The surface roughness used is the higher end of the DNV-GL recommended range for coastal areas. However, the appropriate roughness for Cowichan Lake may be larger because it is inland, and because it is surrounded by treed mountains.

The first pane of Figure 4 and Figure 5 show the downscaled model winds and measurements at the South Arm and Sa-Seen-Os Point, respectively. While there is substantially more temporal variability in the buoy measurements, the modelled wind data follows the measurements closely.

The downscaled model winds were also evaluated by comparing them to winds measured at the Mesachie Lake Weather Station. This station has data from 2006 to present; however, after the start of 2018 there are frequent data gaps and invalid data that impede detailed analysis. The wind speed measured at this station is quite low, with a dataset maximum of about 7 m/s. For periods where the winds are moderate, there is good agreement between the modelled and measured wind speeds. During high winds, the Mesachie Lake measurements are significantly lower in magnitude than both the wind model and concurrent wind measurements at the South Arm Buoy. This suggests that the differences may be due to local effects, such as sheltering of the anemometer by surrounding trees, but it is not possible to be sure since the siting details are unknown. Given the frequent data gaps, there are significant doubts about the accuracy of the Mesachie Lake Weather Station wind measurements for dates after the start of 2018 and therefore no further investigations have been conducted to reconcile the differences.

Wind roses are shown for the measured and modelled wind velocity at Buoy 1 (South Arm) and Buoy 2 (Sa-Seen-Os Point) are shown in Figure 3. At both locations the distribution of modelled winds reasonably represents the observed distribution; however, there are notable differences. At the South Arm buoy, the modelled winds overpredict the number of occurrences from the west, and underpredict the number of occurrences from west-northwest (WNW) and west-southwest (WSW). A similar pattern is also observed in the Sa-Seem-Os point data. It is unclear from the wind roses; however, how these differences influence the skill of the wave model in predicting wave energy.

Wave Model

Figure 4 and Figure 5 show a comparison of the modelled and measured significant wave height, peak wave period and direction at Buoy 1 and 2. The modelled significant wave heights are based on the downscaled wind fields. The wave conditions are very small, with maximum measured conditions reaching only about 40 cm in significant wave height at the buoy locations. The model estimates follow the measurements well during the Feb 10-13 event, and for many of the smaller events. However, the model does not capture all the temporal variability during smaller wave conditions. For the purposes of this study, this is deemed acceptable, as it is assumed that larger wave conditions will have more impact on the location of the natural boundary.

Figure 6 shows a quantile-quantile plot of significant wave height at the Buoy 1 location, covering the period of January 22 to April 1, 2021. Figure 7 shows the same for Buoy 2. The comparison indicates that the model is doing a good job of representing the distribution of wave heights through the analysis period. These plots indicate (1) that that the wave model is adequately calibrated, and (2) confidence that the full hind-cast is fit for its intended purpose of statistically representing the wave climate on Cowichan Lake.

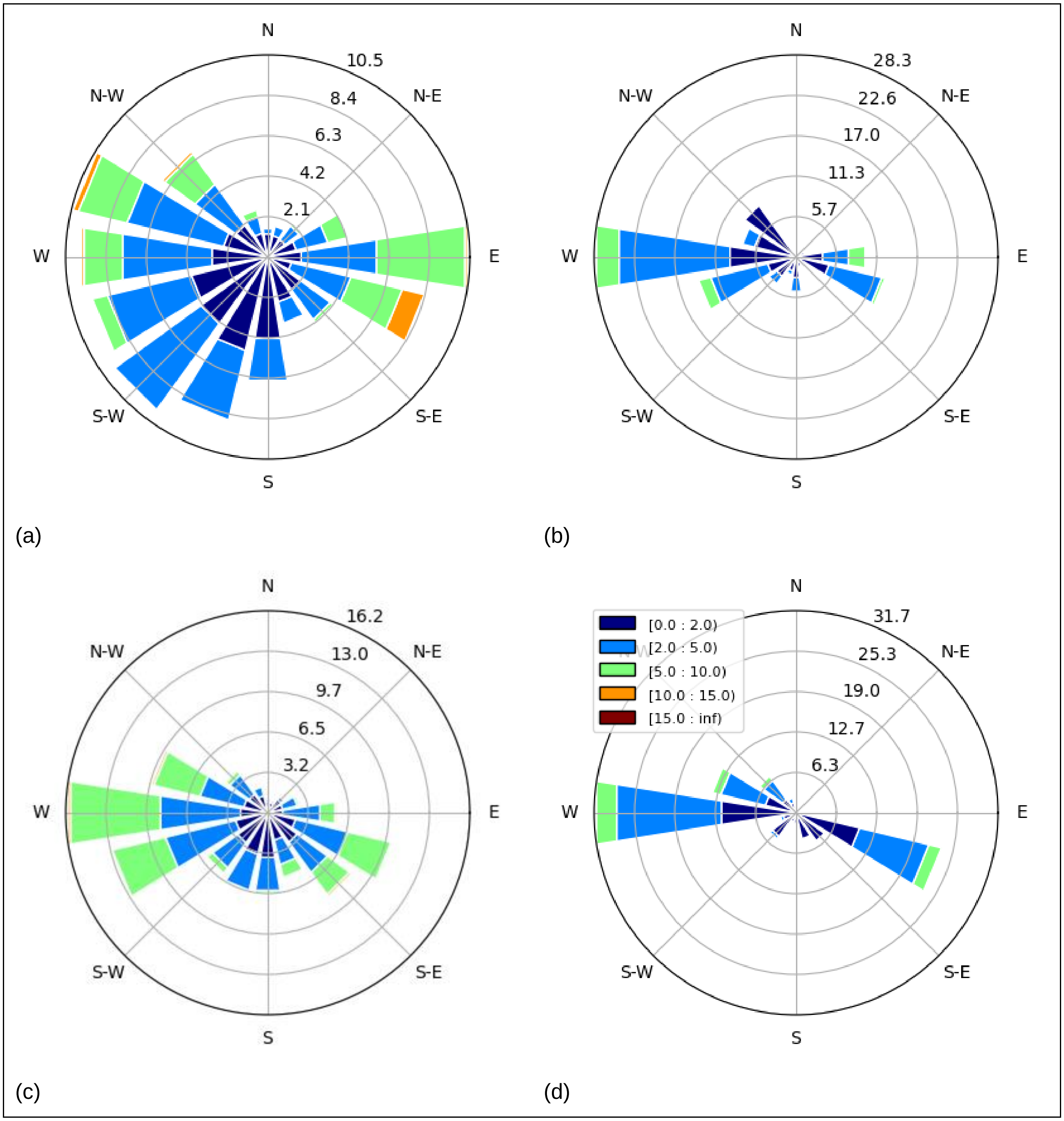

Figure 3: Wind Rose Plots (units: m/s) for the Jan 22 to June 1, 2021 Period
(a) measured at buoy 1, (b) modelled at buoy 1, (c) measured at buoy 2, (d) modelled at buoy 2

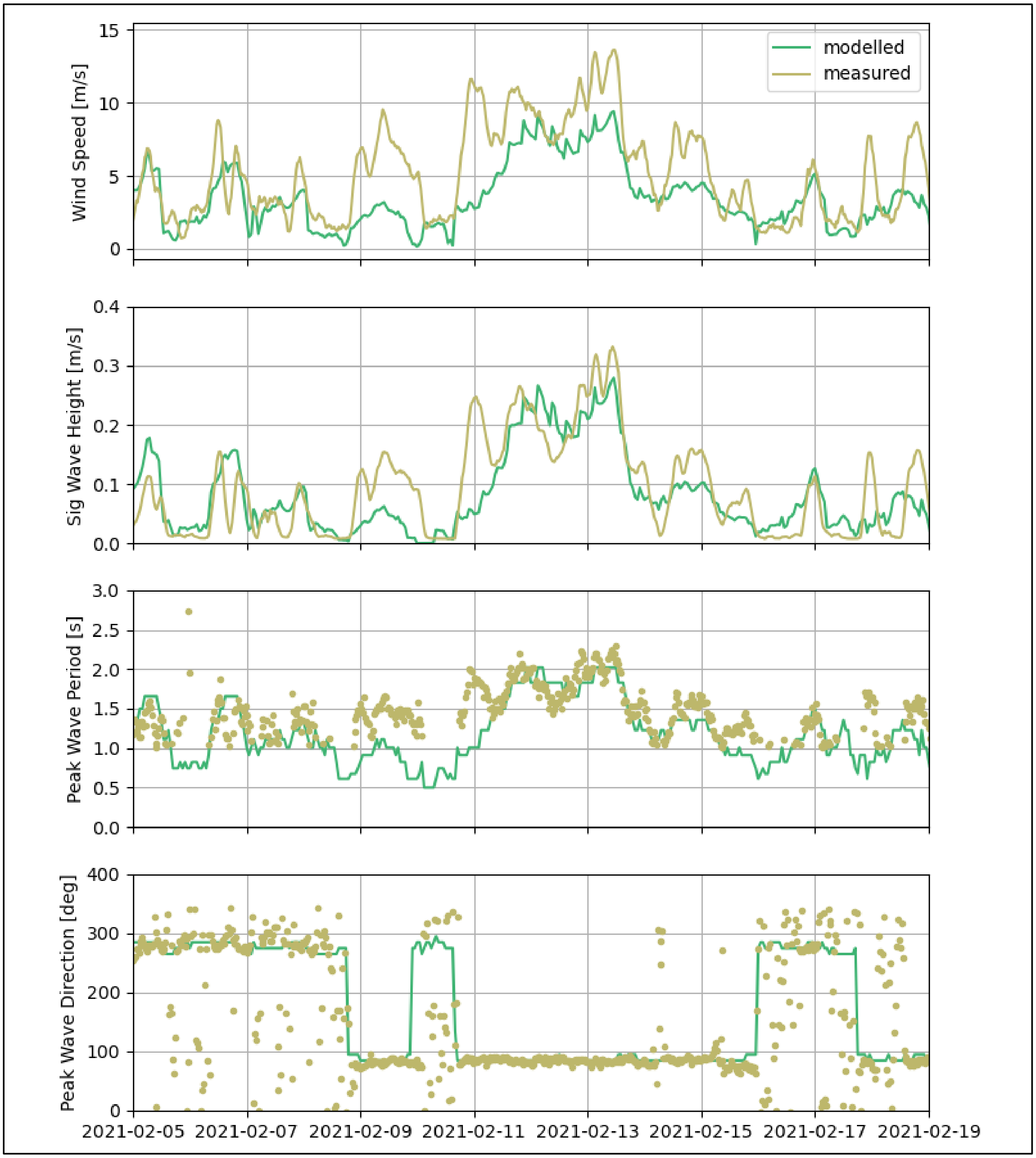

Figure 4: Timeseries comparison of measured and modelled parameters at the location of Buoy 1 (South Arm) for a two-week period in February 2021

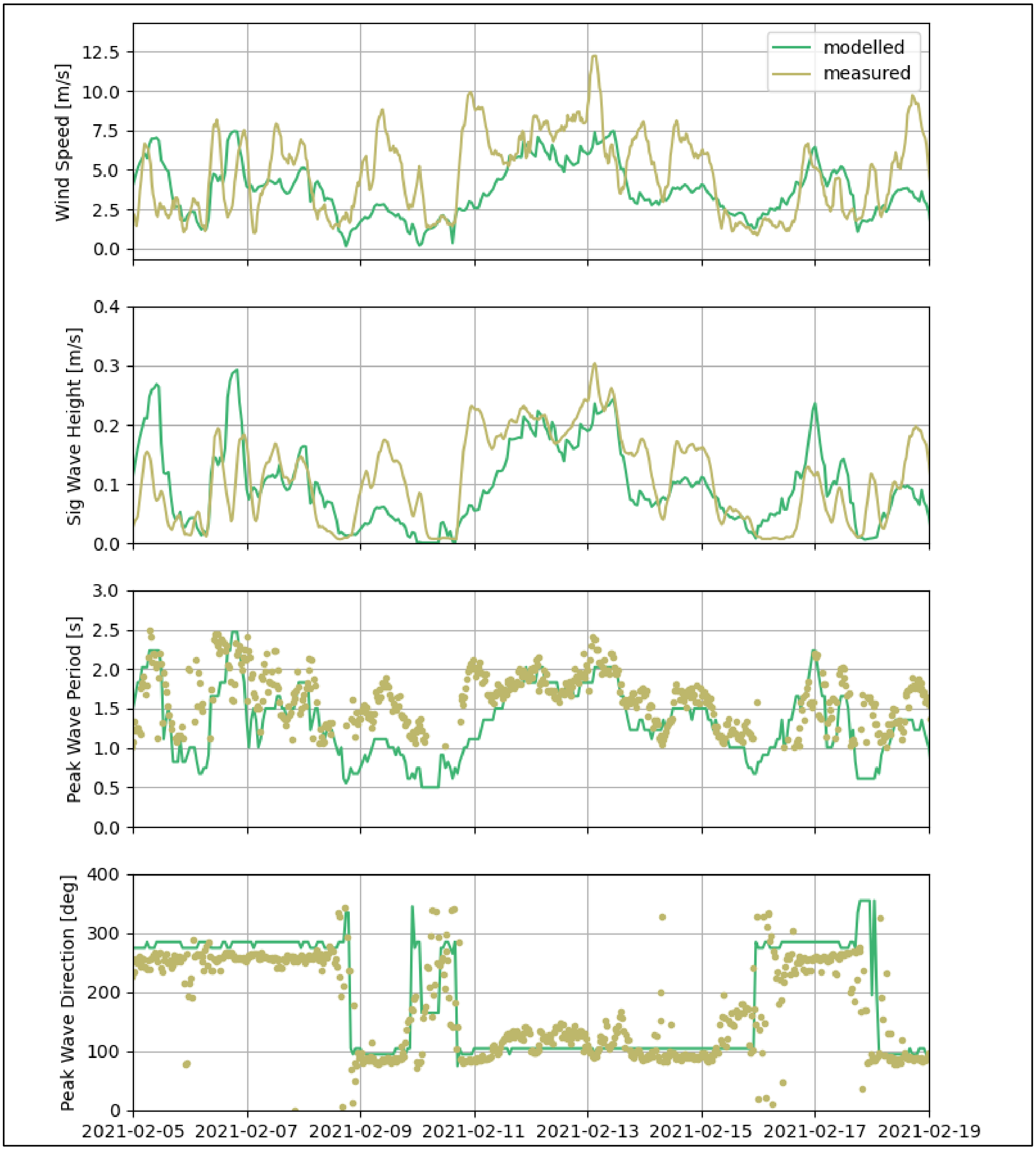

Figure 5: Timeseries comparison of measured and modelled parameters at the location of Buoy 2 (Sa-Seen-Os Point) for a two-week period in February 2021

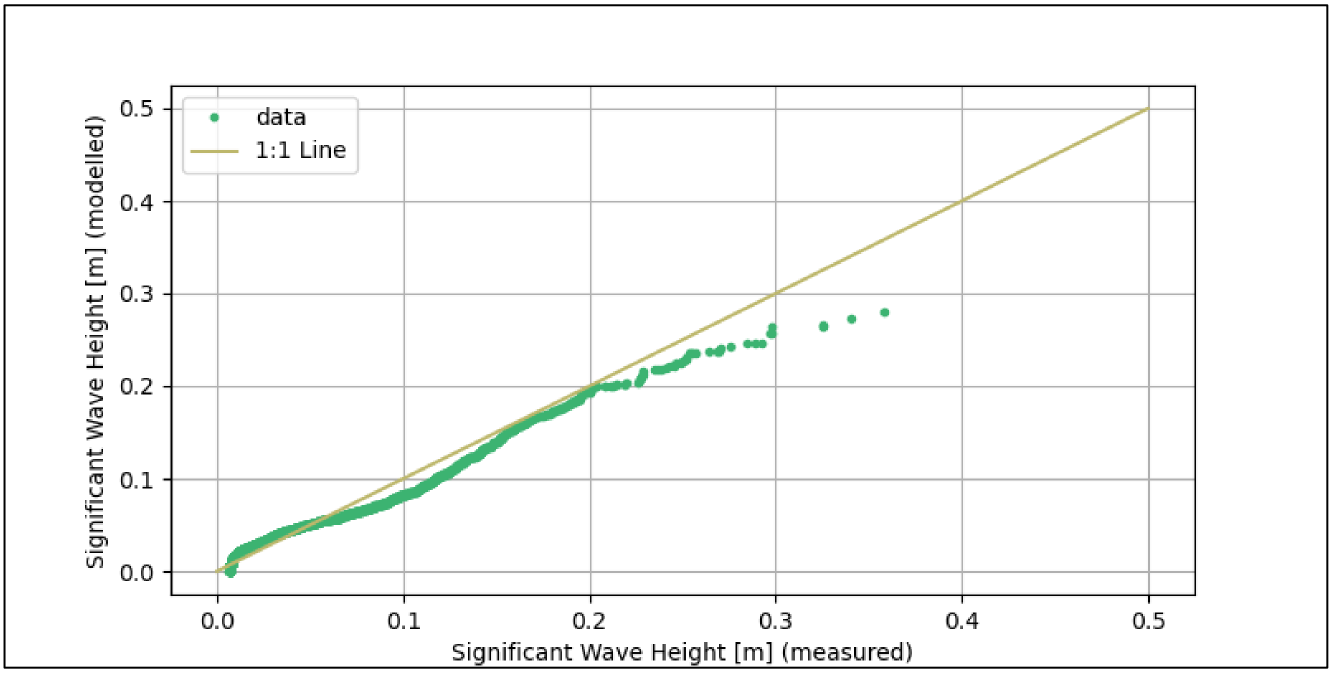

Figure 6: Quantile-quantile Plot of Measured and Modelled Significant Wave Height at Buoy 1 (covering the period of Jan 22 to April 1, 2021)

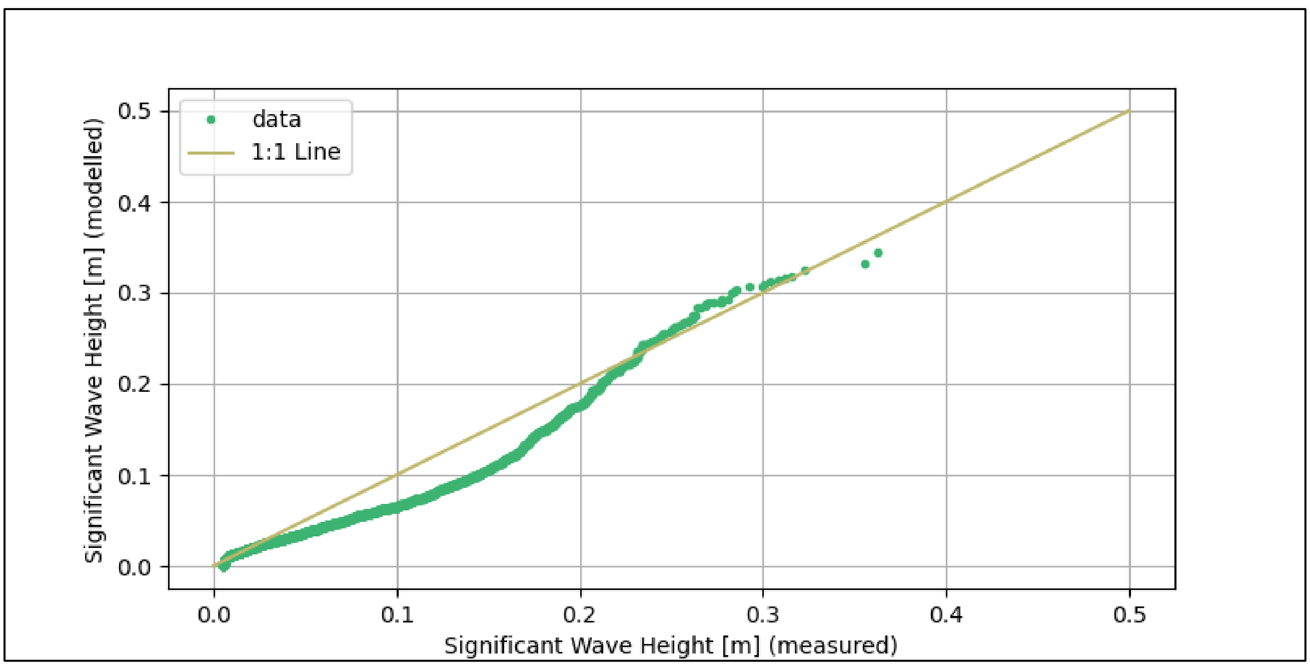

Figure 7: Quantile-quantile Plot of Measured and Modelled Significant Wave Height at Buoy 2 (covering the period of Jan 22 to April 1, 2021)

KERR WOOD LEIDAL
consulting engineers

Appendix E-2

MarineLabs Boat Wave Report

Cowichan Lake Wake Monitoring

Report
November 3, 2021

MarineLabs Data Systems Inc.
Revision 0.5

Executive Summary

MarineLabs CoastScout instruments were deployed in Cowichan Lake on Vancouver Island to measure wakes generated by passing vessels. The instruments were deployed from 2021/01/22 to 2021/09/30. Over this period 3880 wakes were detected in the South Arm of the lake, and 1868 were measured near Saseenos Point.

Each detected wake is summarized by its start and end times, maximum wave height and average wave power. This report is accompanied by CSV files for each buoy, each containing a list of detected wake events. Another CSV file for each location contains results on a per cycle basis, specifically the average wave power for the entire cycle and the average wave power from wakes only.

The results in these CSV files are further processed in this report to produce probability of exceedance curves for the maximum wave height and average wave power of wakes. It was found that, in addition to wake events occurring more frequently, the wake events at South Arm are generally larger than at Saseenos Point. At South Arm, the probability of max wave height exceeding 0.3 m is 8.9%, and the probability of average wave power exceeding 30 W/m is 9.8%. In comparison, the same probabilities of exceedance at Saseenos Point are 3.4% and 3.6% respectively.

Contents

List of Figures

1 Introduction

Two CoastScout instruments were deployed in Cowichan Lake, located on Vancouver Island, for the purpose of measuring the waves from vessel wakes along with naturally occurring wind waves. One instrument was deployed in the South Arm of the lake (48.827807°, -124.129000°) and another near Saseenos Point (48.827807°, -124.129000°), as shown in Figure 1. The instruments were deployed from 2021/01/22 to 2021/09/30. Each instrument measures the wave elevation time series which are transmitted to the MarineLabs CoastAware platform on 30-minute intervals. Vessel wake events are then identified from the time series data.

The goal of the wake analysis is to produce a list of detected wake events containing the start time, end time, maximum wave height and average wave power for each wake event. The overall average power, and the average power from wakes, is also provided with this report on a per-cycle basis. A brief summary of the overall wind and wave climate at each location is also provided with this report.

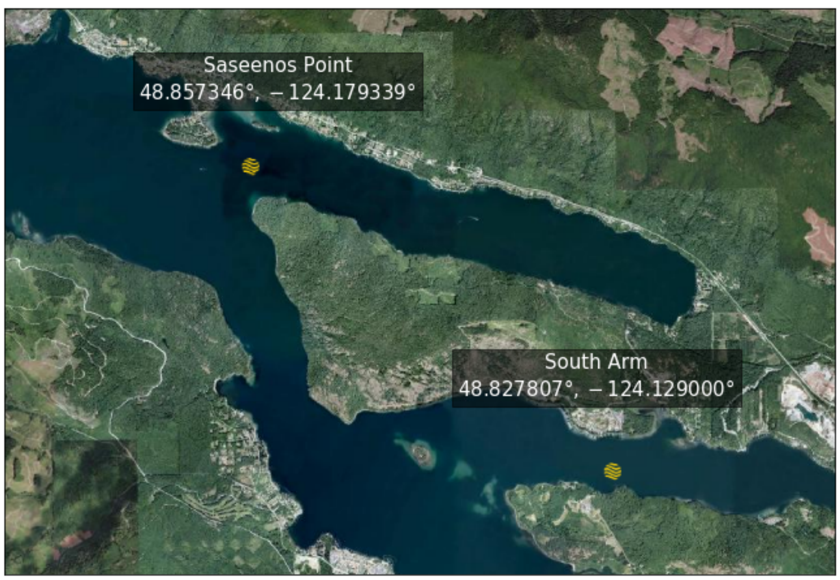

Figure 1: Buoy deployment locations in Cowichan Lake

1.1 CoastScout Technology

Each instrument deployed is a MarineLabs CoastScout unit. This technology was designed and manufactured in Victoria, BC. They are compact, easy to deploy, and transmit the worlds highest resolution marine conditions data to MarineLabs' CoastAware platform. The instrument uses a combination of acceleration, rotational rates, magnetic compass, and GPS for motion measurements that all combine to output position time series that are accurate to 2 cm in wave periods from 1 to 25 seconds. Each instrument also includes a navigation light and features an ultra-sonic wind sensor that provides wind speed, direction and gust.

For this project, CoastScout instruments were installed on 90 cm diameter buoys. The total weight of the buoy and instrument is less than 30 kg. The buoys are typically deployed using 3:2 scope mooring lines of 3/8 sinking line and chain sections to ensure that no vessel propellers are fouled by the mooring lines.

Figure 2: MarineLabs CoastScout buoy.

2 Methodology

2.1 Monitoring Details

Each CoastScout instruments recorded data from the following sensors:

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

The CoastScouts were configured to report on 30-minute intervals. Each report consists of 20 minutes of wave data, collected at 5 Hz. The remaining 10 minutes of each cycle are used to transmit the data. Wind data is collected at 2 Hz for the final 2 minutes of each cycle.

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 CoastScouts 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 time series provides the basis for all the analysis to follow.

2.2 Wind Data Processing

The first step of wind measurement processing is to correct for the pitch and roll motions of the buoy. Then, the wind speed measurements are scaled to 10m using:

$$U(z) = U_m \frac{\ln(z/z_0)}{\ln(z_m/z_0)} \tag{1}$$

U_m is the wind speed measured by the CoastScout at height z_m from the waterline, and z_0 is the surface roughness coefficient, which is set to 1.52×10^{-4} [2].

2.3 Wave Spectrum and Associated Parameters

For a given data cycle, the overall wave system can be summarized by the non-directional wave spectrum $S(f)$, which is the power spectral density of the wave elevation time series calculated using Welch's method. Significant wave height is estimated from the wave spectrum using:

$$H_s \simeq H_{m0} = 4\sqrt{m_0} \tag{2}$$

$$m_n = \int f^n S(f) df \tag{3}$$

Peak period T_p is simply the wave period corresponding to the peak of the wave spectrum. Both significant wave height and peak period are used to create wave histograms for each buoy deployment.

2.4 Vessel Wake Detection

Ocean waves generated by most vessels are made up of the superposition of multiple wave systems. For non-planing 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. In deep water, the transverse and divergent waves combine to form cusp waves in a V-shape with an angle of approximately 35 degrees [1]. The cusp waves are the largest of all the waves in the wake pattern [3].

As vessel speed increases and the vessel beings planing, the transverse waves disappear and the angle of the V-shape formed by the cusp waves decreases below 35 degrees [3].

2.4.1 Time-Frequency Domain Detection

Vessel wakes can be detected using time-frequency detection methods such as spectrograms [1] or wavelet transforms [3][4]. Divergent waves appear as diagonal streaks in the transform, while transverse waves (if present) appear as horizontal streaks [1]. MarineLabs uses the wavelet transform approach. A wavelet transform is calculated for each cycle, and each transform is manually inspected for wake events.

One of the advantages of this approach is that it allows wake events to be detected in the presence of background wind waves. Some sample detected wake events are provided

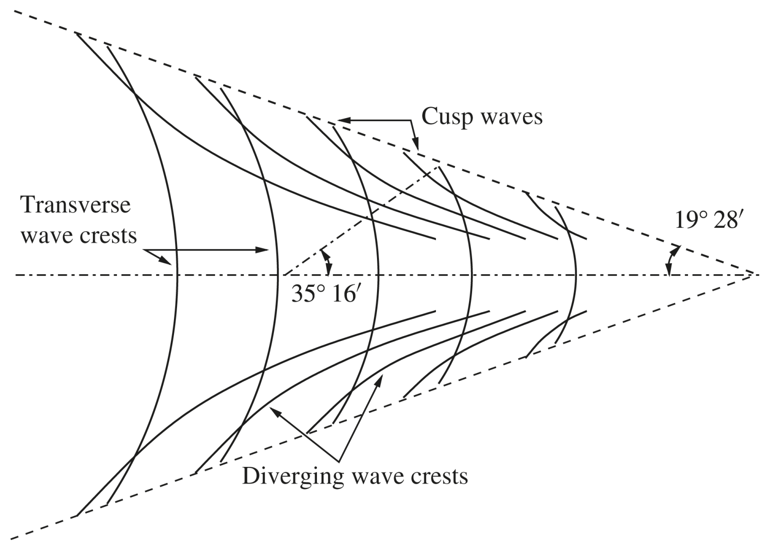

Figure 3: Vessel wake diagram showing divergent and transverse waves [1]

in Appendix A. Figure 22 shows an example of the divergent wave pattern with very small background waves, while Figure 23 shows the divergent waves from another wake event with larger background waves. Note that in Figure 23, the wake event is imperceptible in the wave elevation time series, but can clearly be observed in the wavelet transform.

While this time-frequency based approach is less sensitive to background wind waves, it is still possible to miss wake events if the background wind waves are much larger than the vessel wave heights.

2.5 Maximum Wave Height of Wakes

The wave heights in the wave train produced by a vessel are not constant. Typically there is a maximum wave height when the cusp wave reaches the buoy, preceded and followed by smaller waves corresponding to the transverse and divergent waves. Average wave height is not a suitable metric because it is sensitive to the overall duration of the wake event [5]; a short wake event consisting of only a few waves will have a higher average wave height than a longer wake event lasting for several minutes but with the same maximum wave height. Therefore maximum wave height is used to summarize the size of wakes.

Maximum wave height is obtained by applying zero-upcrossing and downcrossing analyses to the wave elevation time series data. Wave heights that occur during any of the detected wake time intervals are flagged as vessel wakes. The remaining wave heights are classified as wind waves. The maximum wave height for a given wake is then obtained using the results from both zero-upcrossing and downcrossing analyses.

The maximum wave height of wakes is dependent upon multiple factors such as vessel size and draft, water depth and distance from the vessel to the measurement location [6]. A list of predictive models in literature can be found in [6]. Note that wave heights decay as the waves propagate away from the vessel sailing line, so the wave heights measured by the buoy and the wave heights reaching the shoreline will be different.

2.6 Wave Power

Shoreline erosion studies have shown that it is important to consider wave period in addition to wave height, and therefore wave energy and power are better metrics than max wave height for prediction erosion rates [7]. Under deep water assumptions, the average wave power per unit wave crest can be calculated from the wave spectrum $S(f)$ using [8]:

$$\bar{P} = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \tag{4}$$

$$T_e = m_{-1}/m_0 \tag{5}$$

This method is used to calculate the overall average power for each cycle, as well as the average power for each wake event. When calculating the average power for wakes, the wave spectrum is calculated using time series data between the start and end times of the wake event.

3 Cowichan Lake - South Arm Results

Cowichan Lake - South Arm was deployed from 2021/01/22 to 2021/09/30 at coordinates 48.827807°, -124.129000°. The water depth at this location was 45 m. The up time for wind and wave data was 99.7% and 98.3% respectively.

The results in this section are accompanied by two CSV files. The first file, `wake_results.csv`, contains the following results for each detected wake event:

1. wake start time
2. wake end time
3. maximum wave height in the wake event obtained using the zero-crossing analyses
4. average wave power of the wake event obtained using equation (4).

The second file, `cycle_results.csv`, contains the following results on a per cycle basis:

1. cycle start time
2. cycle end time
3. average power of the whole cycle calculated using equation (4)
4. average power of all wake events during the cycle, calculated using equation (4)
5. number of wakes detected during the cycle
6. total duration of wake events

In `cycle_results.csv`, when calculating the average power and total duration of wakes, the time intervals of overlapping wake events are merged together. Average power and total duration are then calculated using the merged intervals. This ensures that the wave power during overlapping wake events does not receive extra weight when calculating the average power from wakes over the entire cycle.

3.1 Wind Summary

Wind measurements over the entire deployment are summarized by the wind rose in Figure 4. Wind directions are relative to true North. The probability of exceedance for wind speed is provided in Figure 5 to provide more resolution into the distribution of wind speeds during the deployment. The results indicate that the probability of wind speed exceeding 10.0 knots is about 12.5%, and that wind speeds above 10 knots occur from the West to North-West, or from the East. The maximum wind speed over the entire deployment is 25.3 knots.

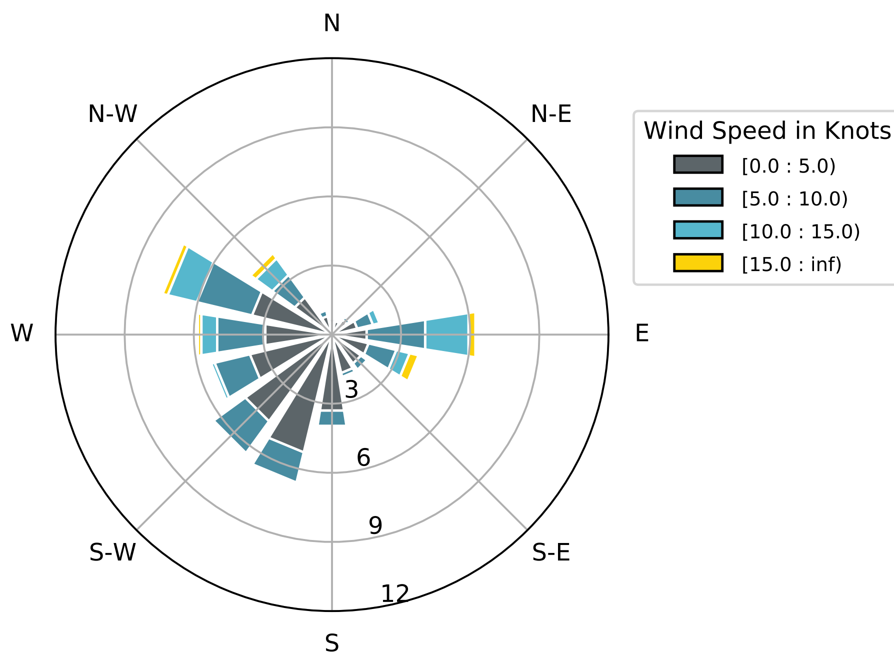

Figure 4: Cowichan Lake - South Arm wind rose.

3.2 General Wave Climate

The overall wave climate, including wind waves and vessel wakes, is summarized by the wave histogram in Figure 6 in terms of significant wave height and peak period. The majority of sea states have a significant wave height less than 15cm and peak period less than 1.5s.

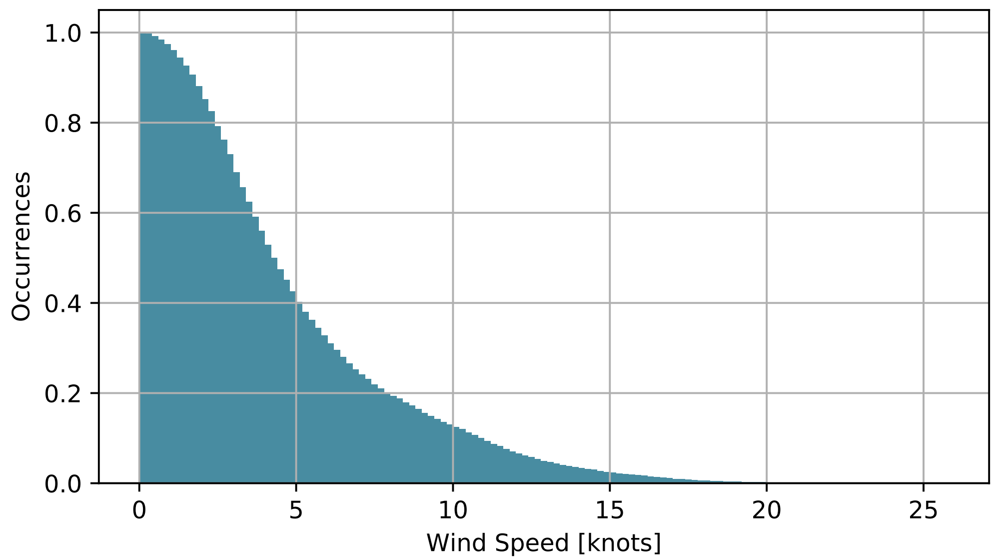

Figure 5: Cowichan Lake - South Arm wind speed probability of exceedance.

3.3 Wake Detection

A total of 3880 wakes were detected over the deployment duration. The monthly wake occurrences are provided in Figure 7. In addition, a histogram of wake events based on time of day is provided in Figure 8. The histograms indicate that the busiest months of the year are July and August, and that the busiest times of day are from 10am to 11am.

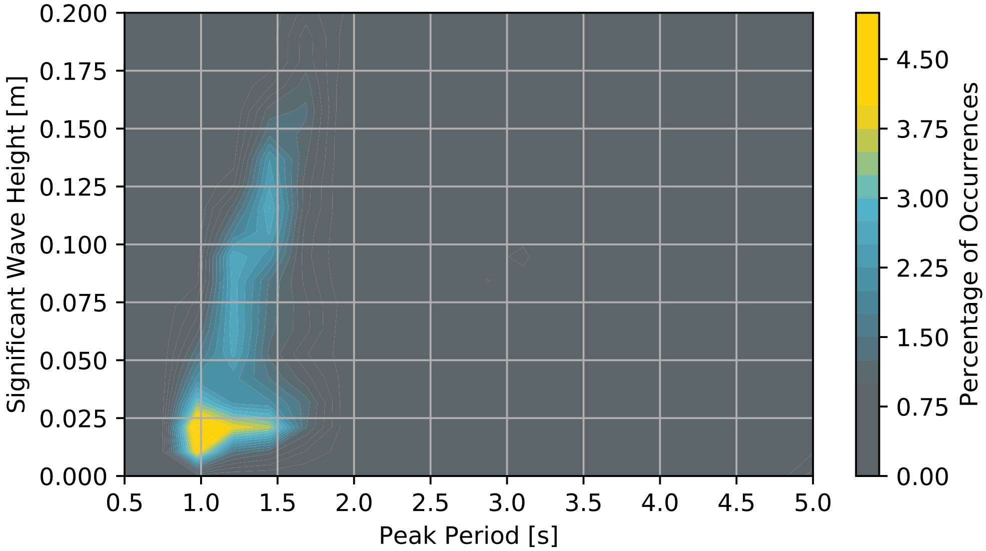

Figure 6: Cowichan Lake - South Arm wave climate histogram.

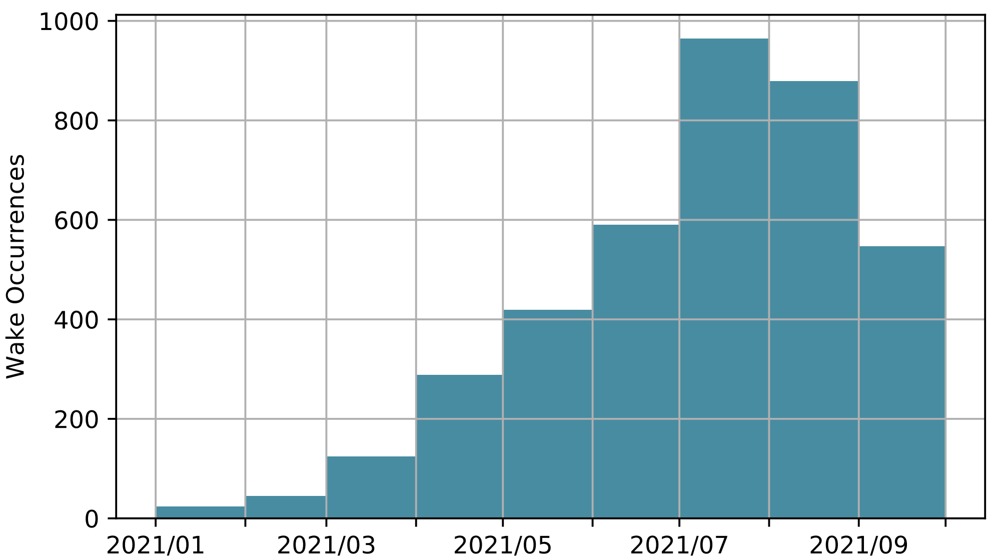

Figure 7: Cowichan Lake - South Arm monthly wake occurrences.

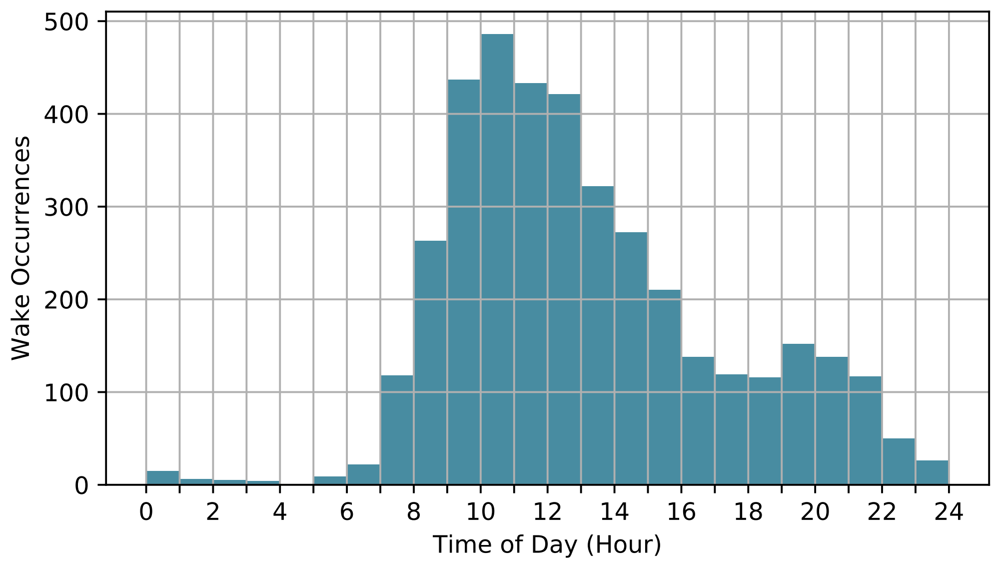

Figure 8: Cowichan Lake - South Arm wake occurrences based on time of day.

3.4 Wake Heights

Zero-upcrossing and downcrossing analyses are performed on the wave elevation time series, resulting in a list of individual waves over the entire deployment duration. Each individual wave is classified as wind-generated or vessel-generated using the start and end times of each detected wake. Histograms of wave height from wind waves and vessel wakes are provided in Figure 10 for both zero-upcrossing and downcrossing analyses.

The zero-crossing results are used to calculate the maximum wave height for each detected wake. Both zero-upcrossing and downcrossing results are used to determine the max wave height for each event. Sample wave elevation time series from the three wake events with the largest wave heights are plotted in Figure 11. The probability of exceedance for max wave height from wakes is shown in Figure 9. Over the deployment period the largest wake had a maximum wave height of 0.64 m. The probability of maximum wave height from wakes exceeding 0.3 m is approximately 8.9%.

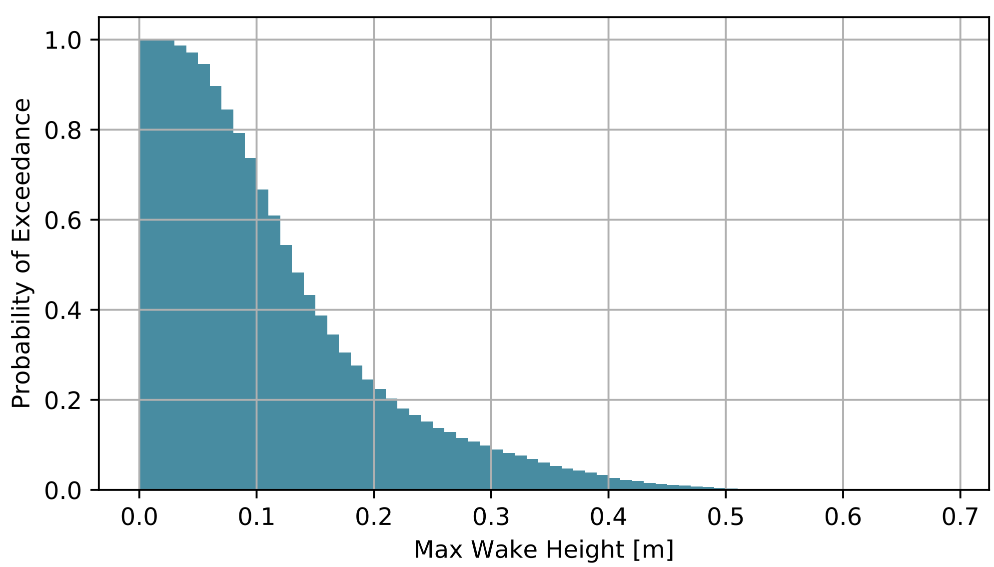

Figure 9: Cowichan Lake - South Arm probability of exceedance for the maximum wave height of wakes.

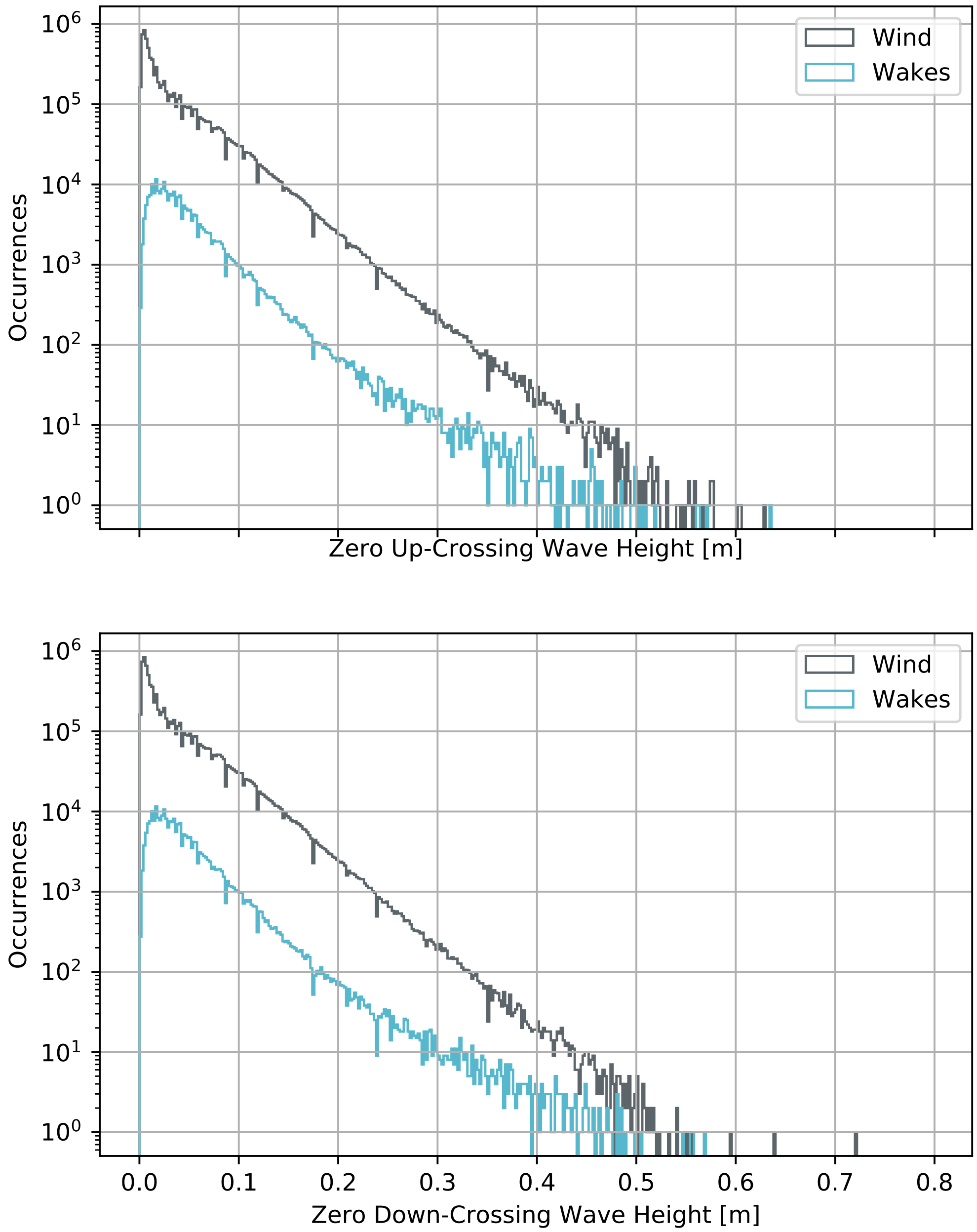

Figure 10: Cowichan Lake - South Arm zero crossing wave height histograms.

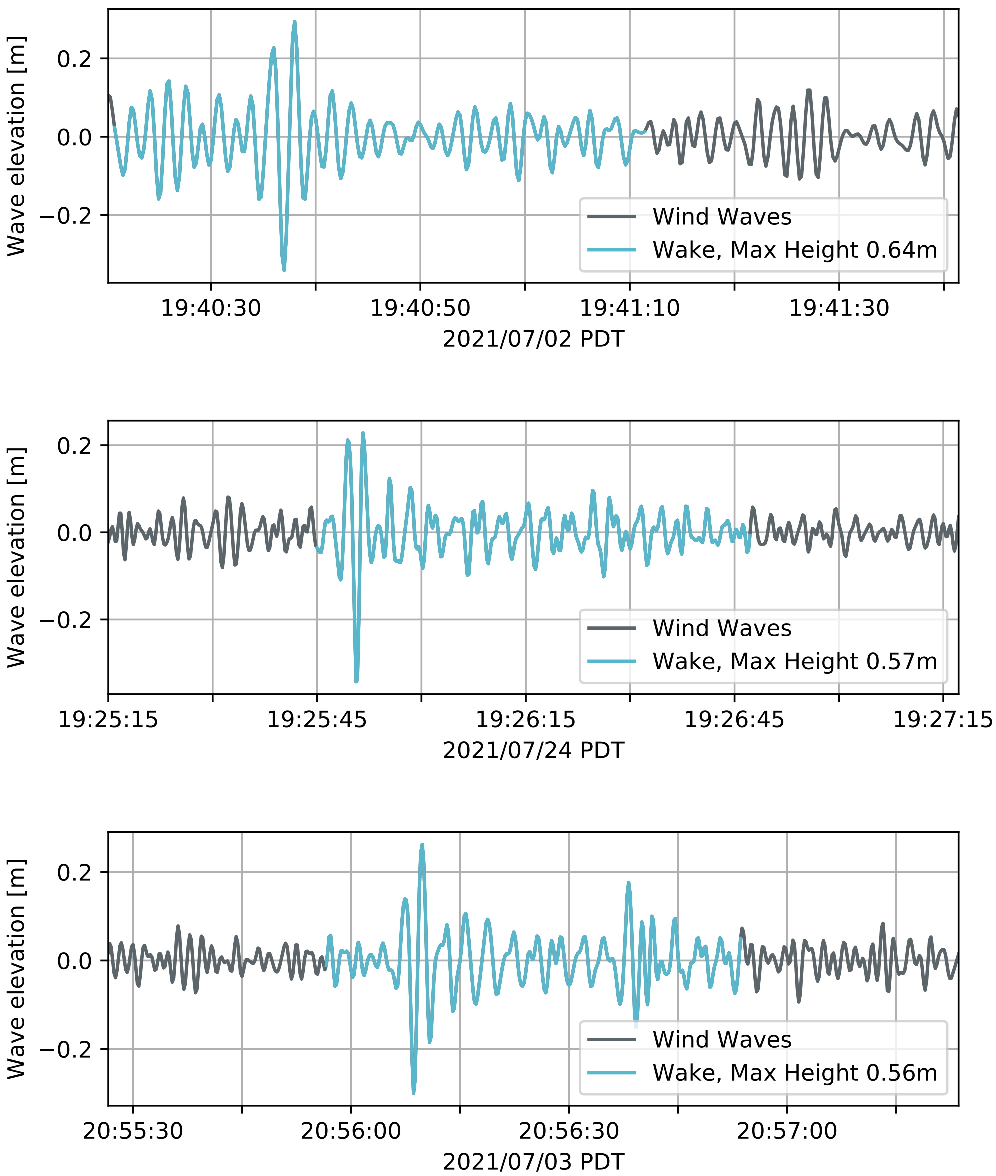

Figure 11: Cowichan Lake - South Arm wave elevation time series for the wake events with the largest wave heights.

3.5 Average Power of Wakes

The average wave power for each wake is calculated using equation (4), where the wave spectrum $S(f)$ is calculated using time series data between the start and end time of each wake. The probability of exceedance of average power for wakes is shown in Figure 12. The largest average wave power of the deployment period is 143 W/m, and the probability of average wave power exceeding 30 W/m is about 9.8%.

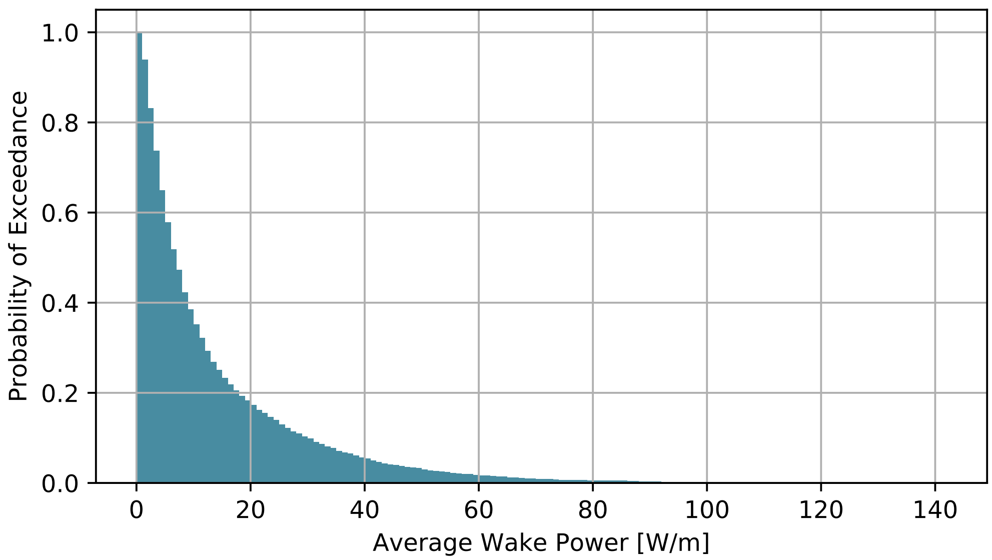

Figure 12: Cowichan Lake - South Arm average wake power histogram.

4 Cowichan Lake - Saseenos Pt. Results

Cowichan Lake - Saseenos Pt. was deployed from 2021/01/22 to 2021/09/30 at coordinates 48.857346°, -124.179339°. The water depth at this location was 45 m. The up time for wind and wave data was 99.8% and 98.2% respectively.

The results in this section are accompanied by two CSV files. The first file, `wake_results.csv`, contains the following results for each detected wake event:

1. wake start time
2. wake end time
3. maximum wave height in the wake event obtained using the zero-crossing analyses
4. average wave power of the wake event obtained using equation (4).

The second file, `cycle_results.csv`, contains the following results on a per cycle basis:

1. cycle start time
2. cycle end time
3. average power of the whole cycle calculated using equation (4)
4. average power of all wake events during the cycle, calculated using equation (4)
5. number of wakes detected during the cycle
6. total duration of wake events

In `cycle_results.csv`, when calculating the average power and total duration of wakes, the time intervals of overlapping wake events are merged together. Average power and total duration are then calculated using the merged intervals. This ensures that the wave power during overlapping wake events does not receive extra weight when calculating the average power from wakes over the entire cycle.

4.1 Wind Summary

Wind measurements over the entire deployment are summarized by the wind rose in Figure 13. Wind directions are relative to true North. The probability of exceedance for wind speed is provided in Figure 14 to provide more resolution into the distribution of wind speeds during the deployment. The results indicate that the probability of wind speed exceeding 10.0 knots is about 20.5%, and that wind speeds above 5 knots are primarily from the West. The maximum wind speed over the entire deployment is 25.4 knots.

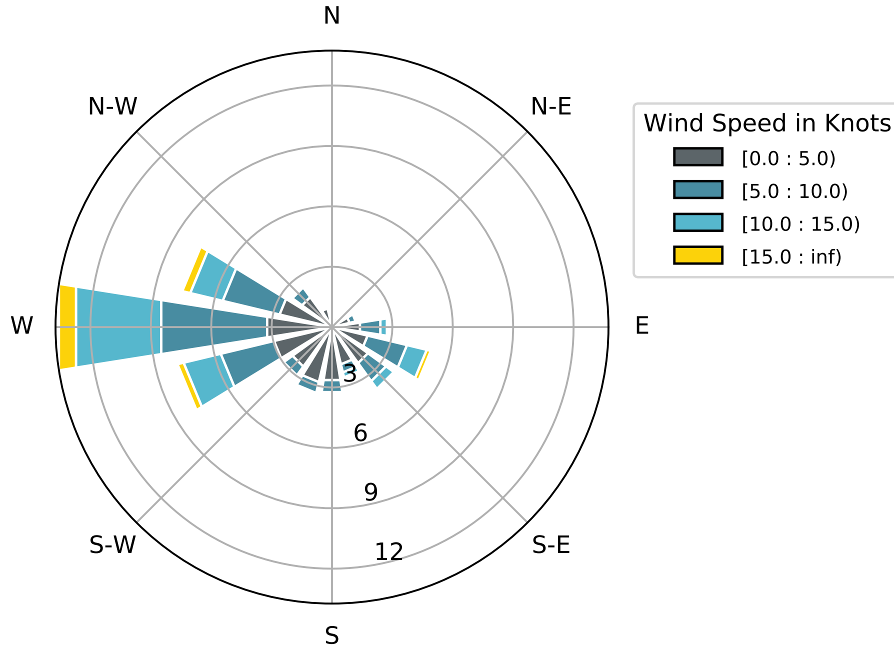

Figure 13: Cowichan Lake - Saseenos Pt. wind rose.

4.2 General Wave Climate

The overall wave climate, including wind waves and vessel wakes, is summarized by the wave histogram in Figure 15 in terms of significant wave height and peak period. The majority of sea states have a significant wave height less than 15cm and peak period less than 1.7s.

4.3 Wake Detection

A total of 1868 wakes were detected over the deployment duration. The monthly wake occurrences are provided in Figure 16. In addition, a histogram of wake events based on time of day is provided in Figure 17. The histograms indicate that the busiest month of the year is August, and that the busiest times of day are from 10am to 11am.

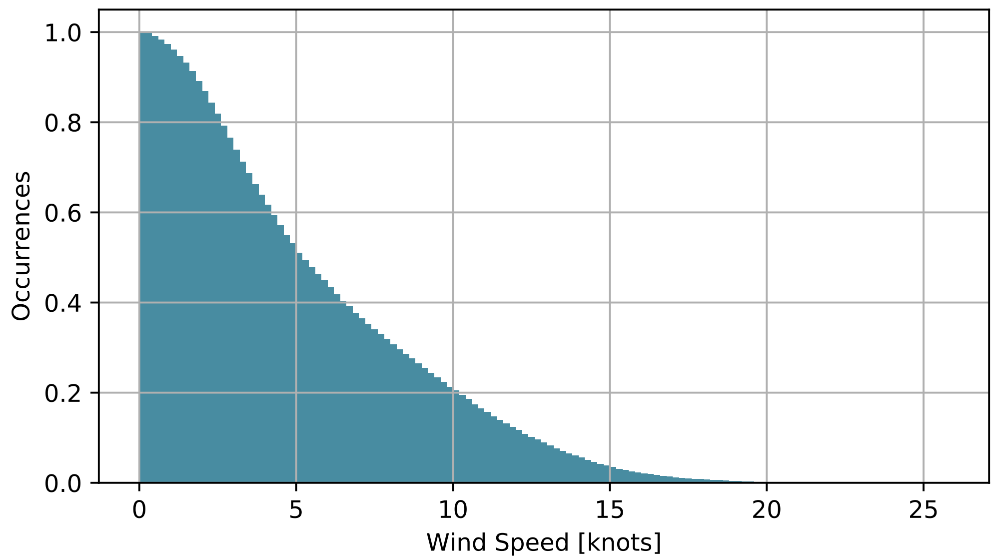

Figure 14: Cowichan Lake - Saseenos Pt. wind speed probability of exceedance.

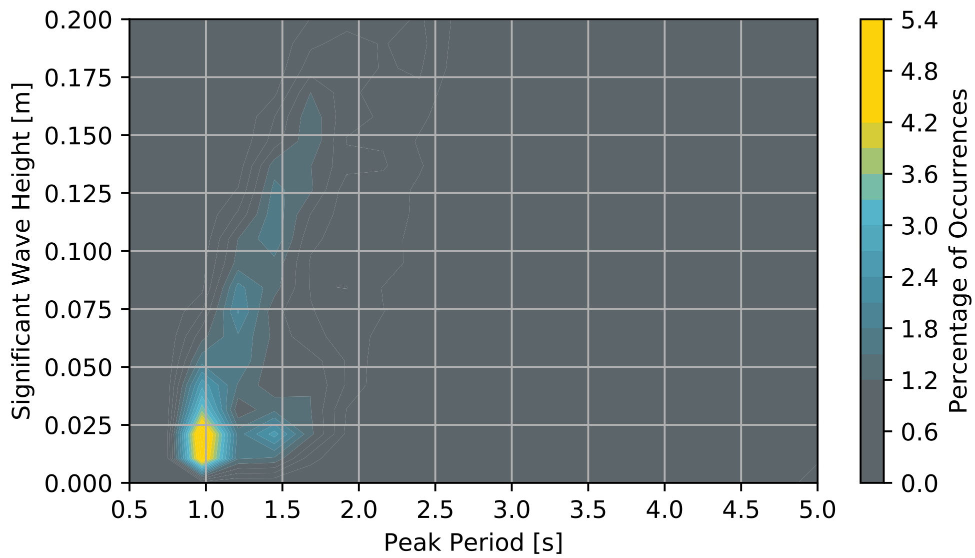

Figure 15: Cowichan Lake - Saseenos Pt. wave climate histogram.

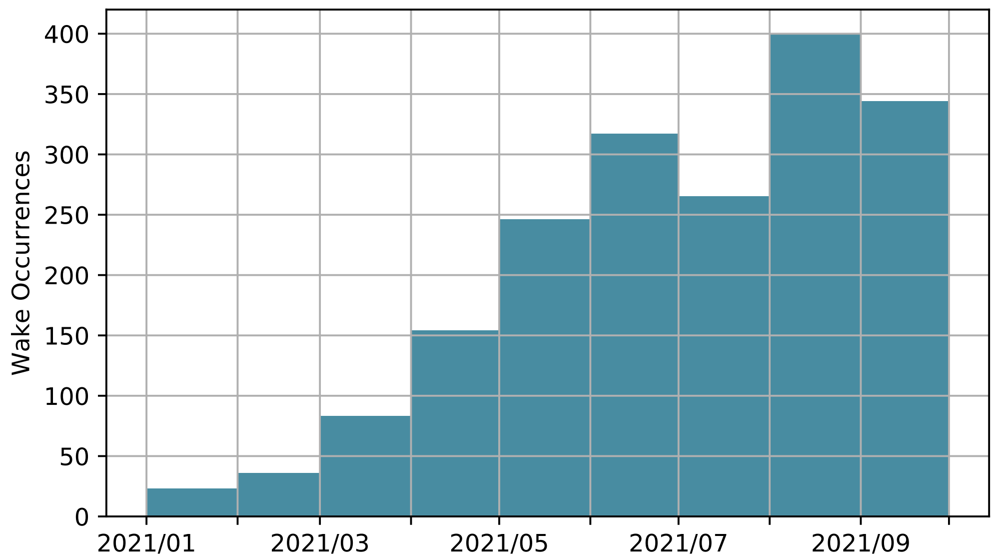

Figure 16: Cowichan Lake - Saseenos Pt. monthly wake occurrences.

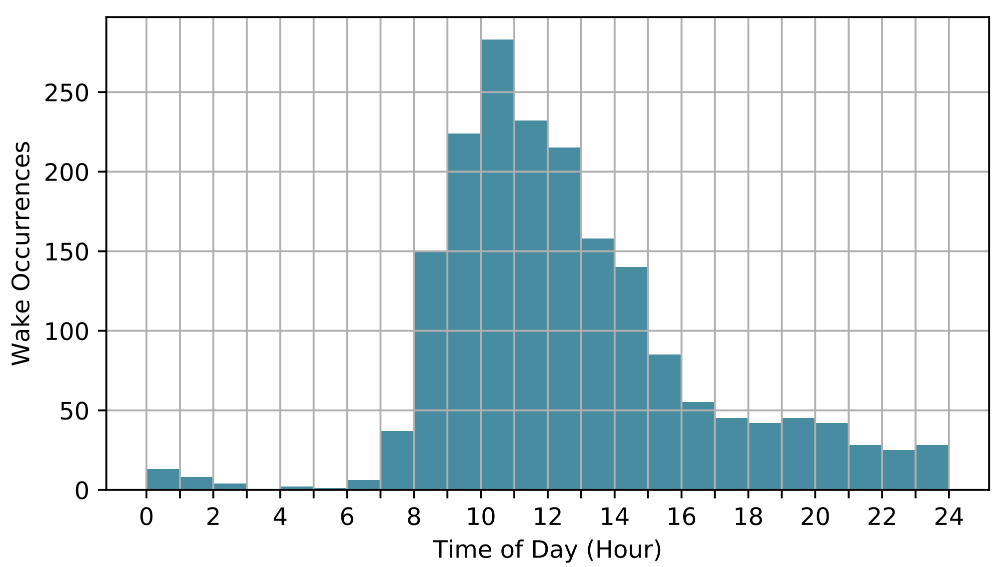

Figure 17: Cowichan Lake - Saseenos Pt. wake occurrences based on time of day.

4.4 Wake Heights

Zero-upcrossing and downcrossing analyses are performed on the wave elevation time series, resulting in a list of individual waves over the entire deployment duration. Each individual wave is classified as wind-generated or vessel-generated using the start and end times of each detected wake. Histograms of wave height from wind waves and vessel wakes are provided in Figure 19 for both zero-upcrossing and downcrossing analyses.

The zero-crossing results are used to calculate the maximum wave height for each detected wake. Both zero-upcrossing and downcrossing results are used to determine the max wave height for each event. Sample wave elevation time series from the three wake events with the largest wave heights are plotted in Figure 20. The probability of exceedance for max wave height from wakes is shown in Figure 18. Over the deployment period the largest wake had a maximum wave height of 0.49 m. The probability of maximum wave height from wakes exceeding 0.3 m is approximately 3.4%.

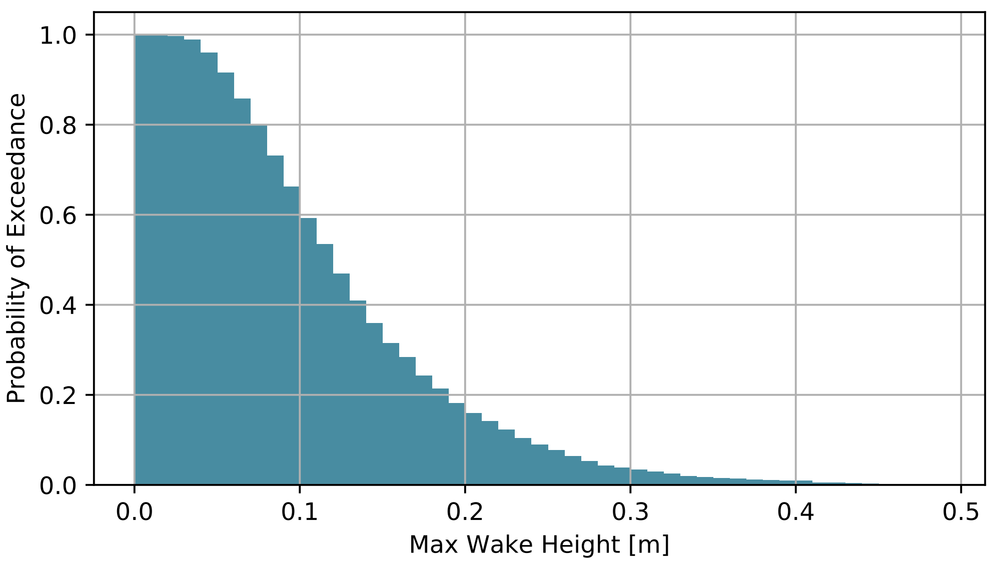

Figure 18: Cowichan Lake - Saseenos Pt. probability of exceedance for the maximum wave height of wakes.

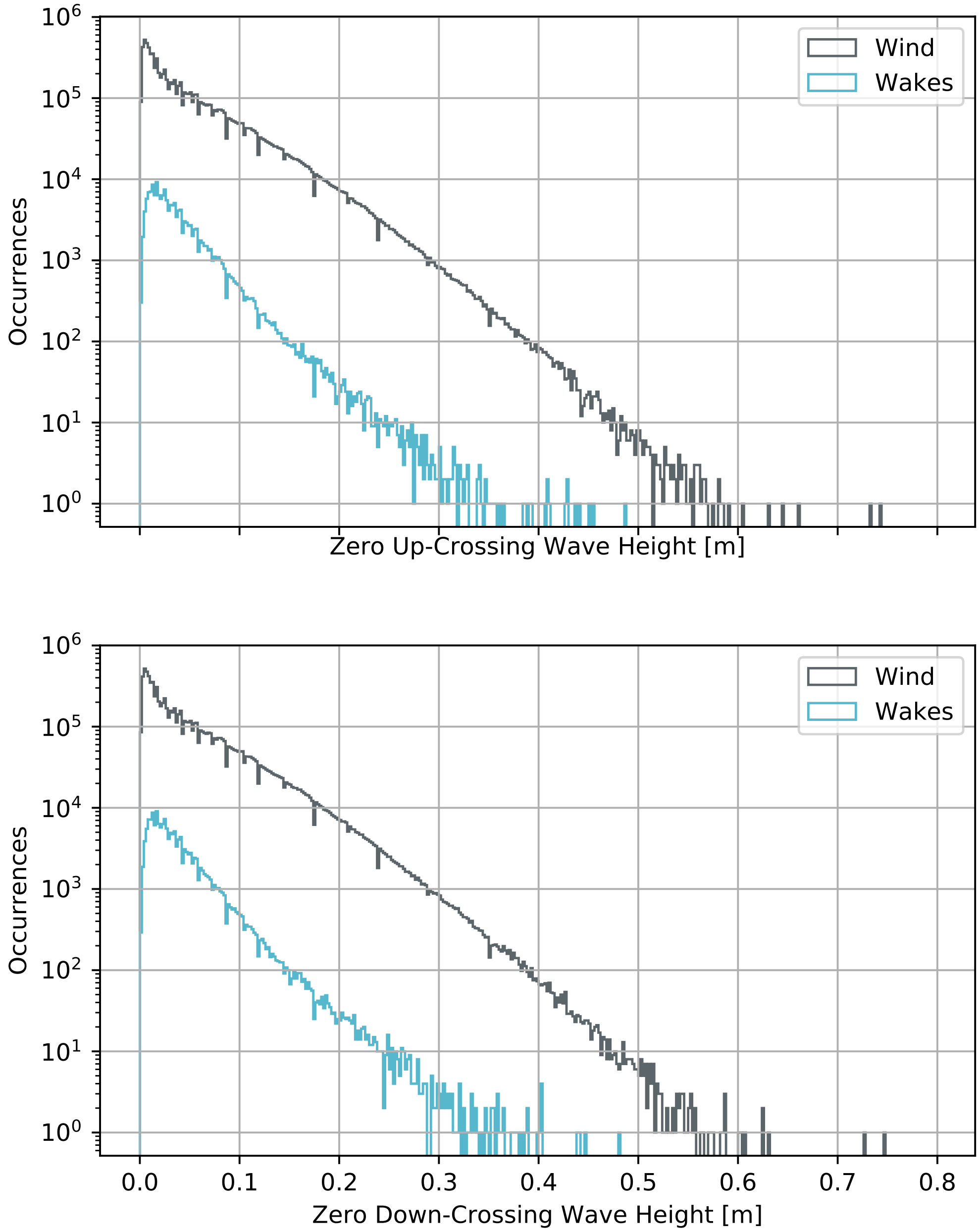

Figure 19: Cowichan Lake - Saseenos Pt. zero crossing wave height histograms.

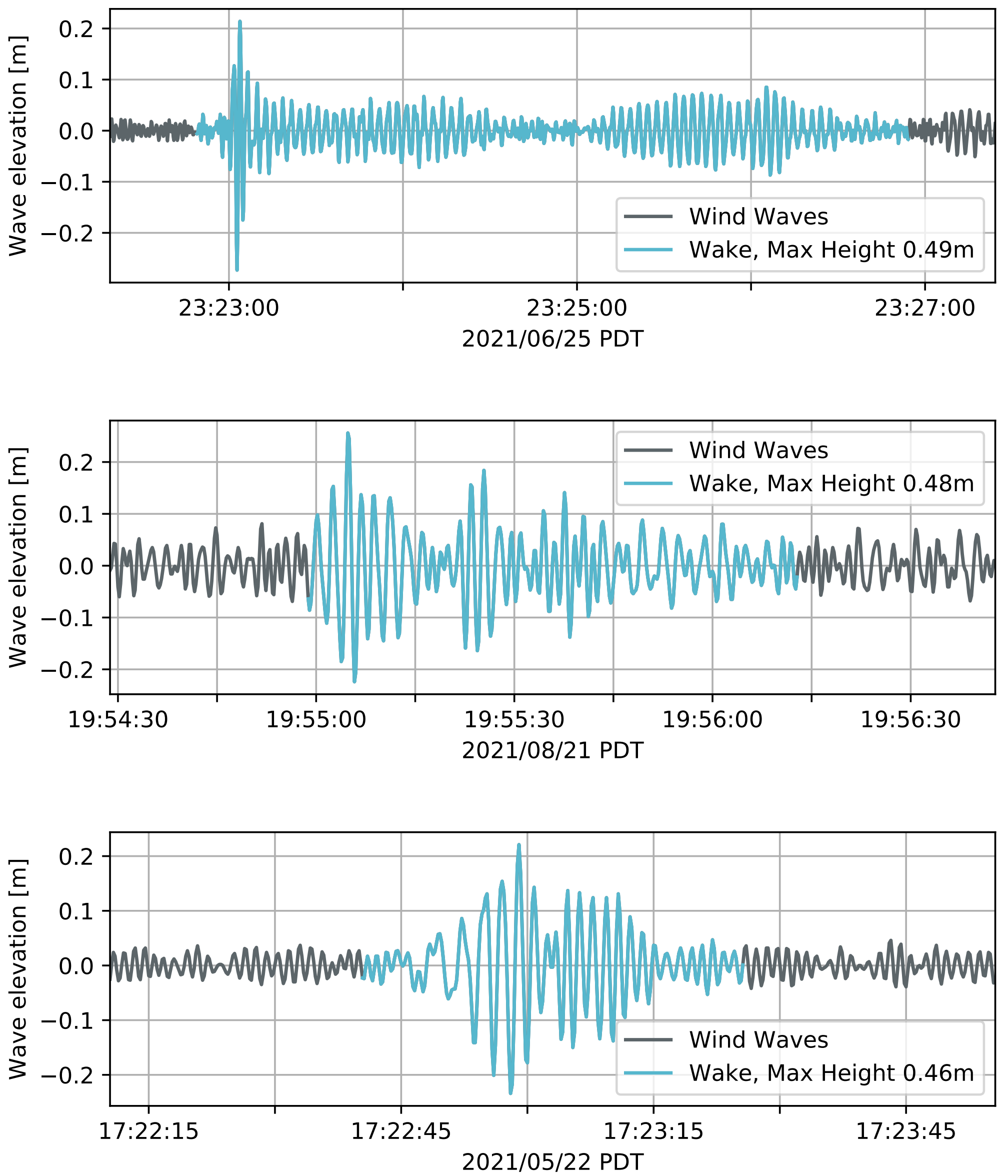

Figure 20: Cowichan Lake - Saseenos Pt. wave elevation time series for the wake events with the largest wave heights.

4.5 Average Power of Wakes

The average wave power for each wake is calculated using equation (4), where the wave spectrum $S(f)$ is calculated using time series data between the start and end time of each wake. The probability of exceedance of average power for wakes is shown in Figure 21. The largest average wave power of the deployment period is 111 W/m, and the probability of average wave power exceeding 30 W/m is about 3.6%.

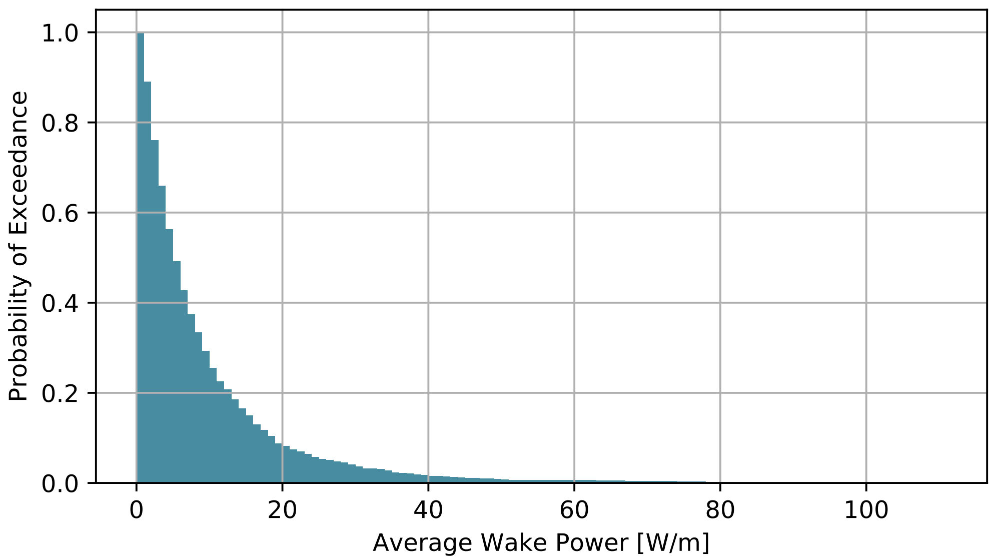

Figure 21: Cowichan Lake - Saseenos Pt. average wake power histogram.

5 Conclusions

Two CoastScout instruments were deployed in Cowichan Lake, one in the South Arm of the lake and another near Saseenos Point. The instruments were deployed from 2021/01/22 to 2021/09/30. Wave elevation time series data was used to detect vessel wakes over the deployment period.

A total of 3880 were measured at the South Arm location, while a total of 1868 were measured near Saseenos Point. At both locations, the busiest time of day was from 10 to 11am. The month with the most wake events was July for the South arm location, and August for Saseenos Pt.

In addition to detecting a larger number of wakes, the maximum wave height and average wave power of the wakes at South Arm are generally larger than at Saseenos Point. The probability of max wave height exceeding 0.3 is 8.9% at South Arm but only 3.4% at Saseenos Point. Similarly, the probability of average wake power exceeding 30 W/m is 9.8% at South Arm and 3.6% at Saseenos Point.

When interpreting the wake results it is important to acknowledge that the vessel wake detection algorithm can miss wake events when there are large wind waves. Therefore the likelihood of a wake event being missed increases with wind speed. The probability of wind speed exceeding 10.0 knots is larger at Saseenos Point than at South Arm (20.5% versus 12.5%). Therefore Saseenos Point may have a larger number of missed wake events.

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A Sample Wake Detection Results

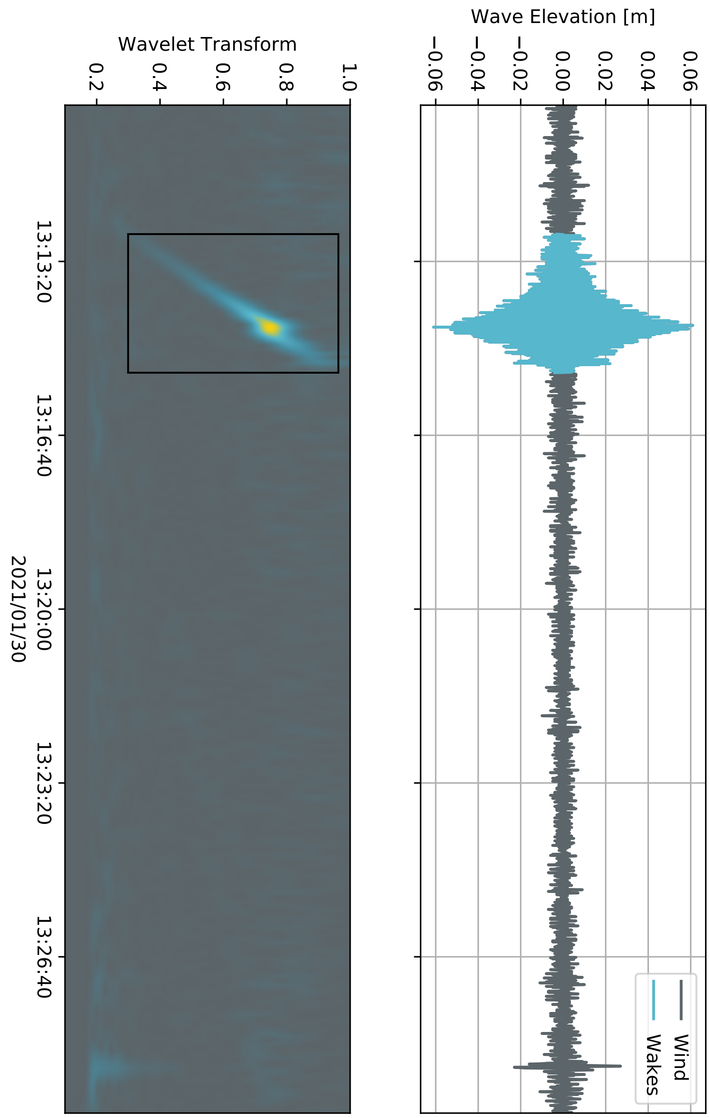

Figure 22: Sample of a detected wake event with low background wind waves.

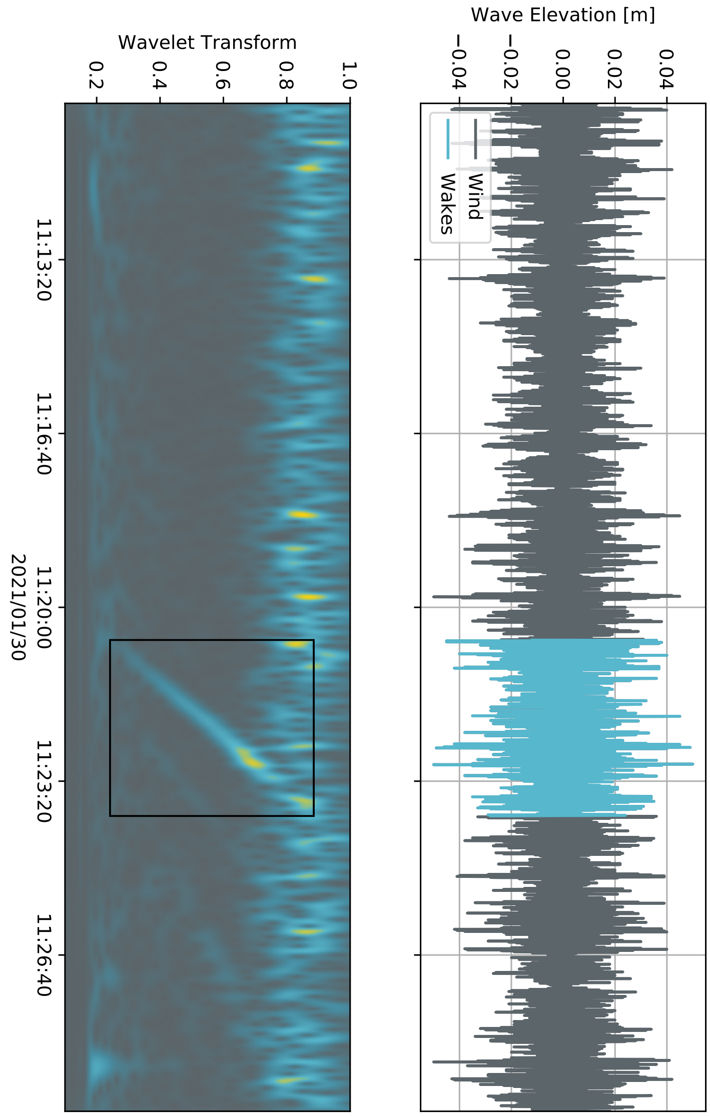

Figure 23: Sample of a detected wake event with high background wind waves.