Survey and numerical model analysis for siting kilowatt-scale tidal turbines

Robert J. Cavagnaro, Jim Thomson, Trent Dillon, Andy Stewart, Taiping Wang, and Zhaoqing Yang

Abstract—**The results of a Finite Volume Coastal Ocean Model of a narrow inlet were used to determine three potential deployment locations for an array of killowatt-scale cross-flow tidal turbines. A single day vessel-based acoustic Doppler current profiler survey was then conducted to more finely resolve differences in power and deployment suitability for each of the sites. Substantial variation in kinetic power density exists between the locations, separated by no more than 300 m, due to complex bathymetry of the site. Both the model and survey indicate the same location as most suitable for deployment. Average relative error in speed magnitude between the model and measurements is less than 10%.**

Index Terms—**ADCP Survey, FVCOM, Micro-Siting, Model & Measurement Comparison.**

I. Introduction

KILOWATT-scale tidal turbines, while inappropriate for commercial utility applications, are under consideration for powering highly specialized marine markets and users. Of these, Naval assets and forward-deployed outposts are especially appealing candidates for being powered by small turbines. Specifically, the inherent benefits of vertically-oriented cross-flow turbines (for which the axis of rotation is perpendicular to the direction of flow, as shown in Fig. 1) overlap with hypothetical mission requirements of device simplicity (high reliability), operation in low to moderate flow speeds (broad applicability), and relatively low rotation rates (lower environmental impact). However, as the technology remains in 'pre-commercial' development, utility for such applications is unproven.

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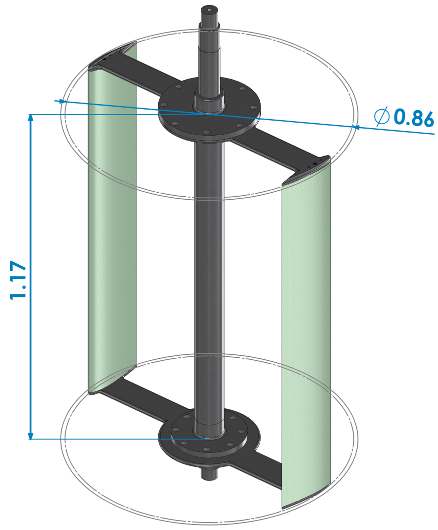

Fig. 1. Rendering of field-scale cross-flow turbine with dimensions in meters.

Typical avenues of research to advance cross-flow turbine technology center on improving system performance and reliability. While critical, these developments do not directly address the operational readiness of systems for Naval applications. The broader goal of this work is to hasten deployability of kilowatt-scale marine turbines by focusing development on deployment, operation, and maintenance. Associated activities will culminate in a demonstration array of a pair of cross-flow turbines generating electricity while deployed at a test site at the inlet of Sequim Bay, WA, USA. The deployment will leverage experience and infrastructure of the Pacific Northwest National Laboratory's (PNNL) Marine Sciences Lab (MSL), which has been developing the site for such applications. Adjacent to MSL, the area is well-studied, sparsely trafficked, relatively shallow, and offers moderate current speeds through a narrow constriction. A satellite image of the location is shown in Fig. 2. Notable landmarks include MSL's dock, Travis Spit, and The Middle Ground. The bay's inlet, narrowing to 200 m to the North of Travis Spit, maintains constriction as it bends south past the dock before fanning out around The Middle Ground.

The site's existing pre-permitted area adjacent to the MSL dock has been used as a testing ground for various environmental monitoring sensor platforms. This area, however, does not extend far enough into the inlet to experience swift flow and its existing permits do not cover operation of a turbine. Therefore, a new, faster site for which the proper permits and leases would be

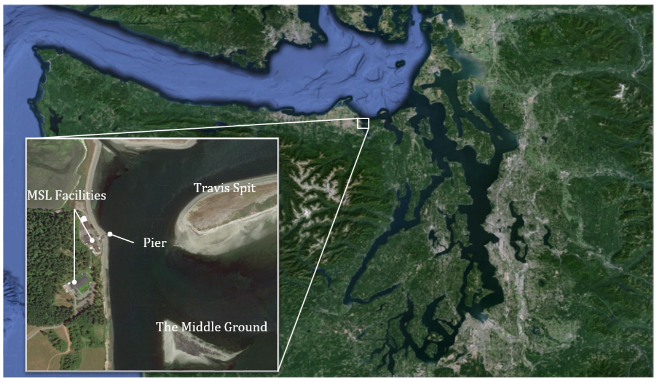

Fig. 2. Satellite image of the inlet of Sequim Bay, inset in image of western Washington State, USA.

acquired is required. The process of determining and specifying the exact location for turbine deployment can be described as 'micro-siting', as the footprint of the site is known but locations of devices within must be identified [1].

The siting process involved three distinct phases described herein: numerical modeling leading to candidate site identification, a vessel-based ADCP survey to compare these, and an analysis and verification phase to close the loop between model and survey. Relevant background is provided in the following section, followed by a description of the methods employed, a summary of results, discussion, and statement of conclusions.

II. Background

Given the dependence of power available to a tidal turbine on the cube of flow speed, the identification of the fastest currents in a region of interest is paramount for commercial success. Therefore, the majority of tidal resource characterization endeavors to date have focused primarily on mean velocity, with secondary analyses of factors such as water level and peak speed [2]. Similarly, investigations of turbulence at tidal energy sites are conducted to establish loading conditions expected to impact turbines [3]. Micro-siting of turbines within a broader site is generally conducted to identify array layouts leading to maximum energy extraction or financial return [1]. However, no studies identified have considered holistic characteristics leading to selection of a preferred site to study deployment, operation and maintenance of turbines.

Extended records of tidal currents in high-energy areas are sparse due to the inherent difficulty of measurement campaigns therein. Consequently, numerical modeling for resource assessment is often conducted as an initial, wide-ranging, lower cost, and reduced risk precursor or alternative to field observations. Several modeling methods accompanied by validation studies have been conducted at potential tidal energy sites around the globe. Carballo et al. [4] compared a depth-averaged model of a tidal estuary created by a finite difference solution to the baroclinic Navier-Stokes and transport equations to measurements from a single, bottom-mounted acoustic Doppler current profiler (ADCP) over seven days. Work et al. [5] compared output from the three-dimensional Regional Ocean Modeling System (ROMS) of an estuary system to both an ADCP transect survery and bottom mounted deployment. Karsten et al. [6] evaluated two resolutions of a Finite Volume Coastal Ocean Model (FVCOM) of the Bay of Fundy with measurements from many ADCPS sampling for week-long periods. To our knowledge, this work represents the first comparison of an FVCOM model of a potential tidal energy site to a single-day vessel-based ADCP survey.

The type of cross-flow turbine selected for this work has been studied at multiple scales and was chosen based on a number of factors indicating suitability for this mission. It has a relatively high coefficient of performance (peak of 0.4), comparable to more common axial-flow designs [7]. It has a single degree of freedom and moving body, leading to simplicity and ease of maintenance. Its aspect ratio (taller than it is wide) and small size result in a small rotational moment of inertia, allowing responsiveness to fast changes in inflow conditions and control actions [8]. Finally, its ability to operate consistently without regard to the direction of flow reduces siting requirements. These characteristics all contribute to ease of deployment, operation, and maintenance.

III. Methods

A. Modeling & Preliminary Site Selection

Preliminary siting began by generating and analyzing the output of a high-resolution hydrodynamic model covering Sequim Bay and its surrounding waters. The Sequim Bay hydrodynamic model is a standalone model developed from PNNL's FVCOM-based Salish Sea Model by significantly refining grid resolutions in the Sequim Bay area [9], [10]. The Sequim Bay model covers the entire Sequim Bay and surrounding intertidal wetlands with an unstructured mesh that has a spatial resolution varying from < 10 m near the entrance channel to 800 m at the open boundary. The open boundary conditions are forced with water level time series from the Salish Sea Model output. The Sequim Bay model, consisting of nearly 50,000 elements and 10 depth layers, resolved velocity for a two month period in 15-minute steps. This output, combined with data from a 1.5 m resolution multi-beam sonar bathymetry survey, resulted in a spatiaotemporal glimpse of flow at the site over two full neap-spring tidal cycles. A heat map depicting expected turbine power output at the site averaged over time generated for the region of interest is shown in Fig 3.

Priorities in micro-siting, keeping project objectives of deployment, operation, and maintenance in mind, were established by a group of experts in turbine/PTO design, permitting, resource characterization, and environmental monitoring. The group identified and assessed metrics associated with (in order of decreasing priority) risk of overturn, power density, bottom slope, ebb/flood asymmetry, depth, velocity shear along the rotor, whether to deploy within the MSL permitted

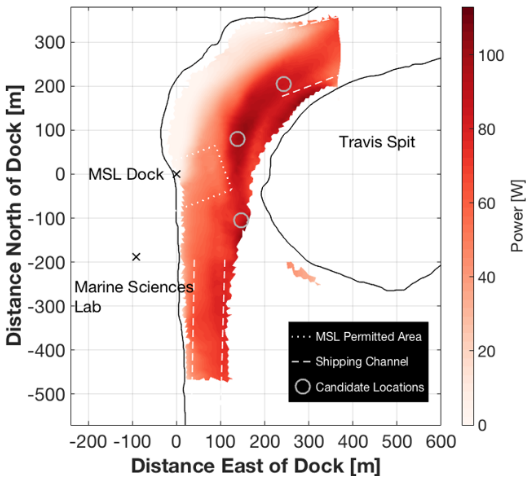

Fig. 3. Simulated turbine power output over 2 months with candidate sites indicated.

zone and proximity to the shoreside point of connection as the nominal considerations in micro-siting for this project. Upon review, many seemingly meaningful factors were found to be imperceptible or incidental to achieving the project goals. Contrary to our original perceptions, expected power output, overhead clearance and mitigating risk of overturn emerged as the salient considerations for site identification.

Siting the turbine within the MSL permitted zone was deemed incidental due to ongoing efforts to permit additional area within the bay for such use. Further, contrary to deployments in larger sites or involving higher capacity devices, capital costs associated with transmitting power are low; maximum distance from the turbines to the point of connection would not exceed 400 meters for any considered location. However, closer proximity was determined to be of benefit, as power transmission voltage is low relative to commercial sites, leading to more substantial loss with distance. Furthermore, evaluating the vertical velocity shear across the turbine rotor, despite implications for increased structural fatigue and losses in power output, was deemed impractical due to the coarse depth resolution of the FVCOM model output relative to the size of the turbine.

Ebb/flood asymmetry, although a major concern for other types of turbines, was deemed incidental because single vertical-axis cross-flow turbines allow for omnidirectional inflow in the horizontal plane. Asymmetry may become a factor when considering the relative placement of turbines in arrays, as evidence suggests strategically locating turbines in close proximity to each other may lead to modest performance gains [7]. However, these gains are expected to be marginal, and losses associated with lack of symmetry may be mitigated by aligning the turbine array with the dominant axis, while positioning the lander orthogonal to the minor axis.

Bottom slope was determined incidental because it is not an intrinsically limiting factor. The seafloor typically steepens to slopes that would hazard the deployment of a turbine foundation (>10%) in near shore regions where depth is already insufficient. More moderate fluctuations in bottom slope (4-9%) might influence risk of overturn or losses in power generation. Consequently, the impact of bottom slope on turbine operation was instead integrated into analysis on the risk of overturn and expected power output.

Similarly, required foundation weight for turbine stability, expected power output and overhead clearance were evaluated. We found foundation weight requirements throughout the inlet to be within the limits of a selected deployment vessel. Consequently, candidate locations were chosen to prioritize power output in regions where there is adequate depth.

Three candidate sites exemplifying combinations of high power and strong ratings for the ancillary factors discussed above were identified. These are denoted herein as the North Site, Central Site, and South Site, and are shown Fig. 3 along with outlines of the pre-permitted MSL zone and vessel lanes. Note the expected average power output (over many tidal cycles) is on the order of 100 W. Highest power is expected at the Central site, followed by the South and North, respectively. Unshaded regions indicate a minimum clearance of 0.5 m to avoid turbine aspiration at low water is not exceeded. Distances to the shoreside point of connection are similar for the Central and South sites at 160 m and 175 m respectively, while the North site is 315 m removed.

B. *Vessel-Based ADCP Survey*

Given the small footprint of the devices (turbine diameter is less than 1 m), variation in the resource characteristics over small spatial distances, perhaps smaller than the resolution of the model, are likely to greatly influence location suitability. Therefore, a subsequent shipboard survey using a 'station keeping' resource characterization method was deemed necessary to increase knowledge and confidence in a siting decision. The method, developed by Palodichuk et al. [11], specifically for identifying relative resource strength between geographically close locations, is performed by maintaining a ship-board ADCP at each location for several minutes, multiple times, bracketing peak tidal flow. It is a faster, cheaper alternative to long-term deployment (and recovery of) a grid of bottom-mounted instrument platforms performing the same function.

Accuracy of the Palodichuk Method for resource characterization was previously estimated by emulating its output using a longer, continuous bottom-mounted ADCP survey. Recommended survey parameters include conducting multiple surveys with at least six observations at each station. Single survey standard error was estimated to be 20% [11]. A five-minute observation at each station was determined to be sufficient to reduce the contributions of turbulence and shifting tide [11].

A single survey was conducted on June 12, 2018, observing velocity at three stations during a greater tide at the beginning of the spring phase of the fortnightly tidal cycle. Locations of the stations are provided in Table I. The survey vessel was a 30 ft boat typically used for local coastal water operations with small crews and payloads. A Teledyne-RDI Workhorse Mariner 1200 kHz ADCP with bottom tracking was mounted to a pole extending off the port side of the vessel to avoid interaction with its wake. The vessel's GPS, heading, pitch and roll sensors are referenced by the ADCP to correct for motion. Instrument settings and deployment parameters are summarized in Table II.

Starting as the tide began to ebb, station was kept at each of the three candidate sites, beginning at the North site. After more than five minutes of measurement, the vessel transited to the Central site, and then the South site before returning to the North site to repeat the cycle. A total of 9 cycles each were completed during ebb and flood. Care was taken by the vessel operator to maintain station as well as possible using GPS position feedback. The survey was paused during slack water conditions.

Raw ADCP output was processed to yield velocity in the fixed earth reference frame (East-North-Up) and passed through a quality control regimen. Measurements in depth bins within 1 m of the seabed or exceeding a velocity of 5 m/s were removed. Subsequently, linear interpolation was used to infer speed at a hub height of 2 m above the seabed. Flow direction was computed using a four-quadrant inverse tangent function applied to East and North measurements. A 50 m radius was used as a station location tolerance; measurements falling within this distance from each intended site were binned. Measurements were then grouped into clusters occurring over $>=$ 5 continuous minutes. Periods of successful station keeping were identified as those satisfying both spatial and temporal conditions. Flow statistics (i.e., mean, standard deviation, etc.) were calculated for these clusters and centered at the median timestamp.

Kinetic power density, defined as

$$KPD = \frac{1}{2}\rho u^3 \tag{1}$$

in which ρ is the density of water and u is velocity, represents the power of flow passing through a plane of 1 square meter cross section. As such, it is a convenient metric to report for tidal energy resource characterization. KPD was calculated by first cubing velocity measurements before taking the mean to avoid biasing the result towards lower values. Second-order polynomials were fit to KPD data for each site for ease of visual comparison.

TABLE I
LOCATIONS FOR SURVEY STATIONS.

Station	Latitude (Deg. N)	Longitude (Deg. E)
North	48.08118	-123.04182
Central	48.08006	-123.04323
South	48.07839	-123.04311

C. Bottom-Mounted ADCP Survey

Following site selection, a multi-sensor instrumentation package was deployed near the Central site.

TABLE II
ADCP SETTINGS.

Parameter	Value	Unit
Transmit Frequency	1228.8	kHz
Bin Size	0.5	m
Number of Bins	24	-
Ensemble Interval	10	s
Pings per Ensemble	12	-

Though not intended to be used for resource characterization, the platform included an ADCP and was configured for this purpose. The instrument (Nortek Signature 500) was set for 1 minute average velocity recording with a bin size of 0.5 m above a 0.5 m blanking distance, resulting in the first viable bin roughly 2 m above the seabed. Data were recorded from March 3, 2019 to April 6, 2019, returning 29 days (with some intermittent outages) of velocity measurements suitable for tidal constituent analysis. This was performed with software package UTide implemented in Matlab [12]. Additionally, the bottom mounted survey provided a longer-term record of peak current and flow direction, useful for benchmarking the single day survey and model.

IV. RESULTS

Key survey results regarding KPD and ability to keep station were critical in selecting an appropriate site and evaluating measurement quality. These are summarized below. Survey results are subsequently compared to FVCOM output at the Central site over the same range of time.

D. Speed and Kinetic Power Density

KPD for each site and iteration is reported in Fig. 4, with mean values reported as 'X' markers. Dots indicate sample median and bars represent the 25th to 75th percentile of the data, with whiskers representing the extent of more extreme measurements not considered outliers. Polynomial fits are to means. Key statistical quantities over ebb and flood and the entire series are summarized in Table III. Variation in the resource at the three sites is significant, particularly during ebb. The strength of current during ebb at the Central site relative to the others results in it having the strongest overall resource despite the lowest overall standard deviation (σ). Maximum recorded speed not considered a statistical outlier is 2.6 m/s, occurring during flood tide at the South site. Cut-in speed, the speed at which the turbines are expected to begin producing power, is anticipated to be 0.5 m/s for the deployment. The central site maintained this minimum value for the longest period of time of the three sites considered.

E. Station Keeping Performance & Bottom Tracking

Complex geography and bathymetry in the inlet to the bay yield large variations in resource as shown above over relatively small distances. Consequently, relevance of the data depends on tight spatial tolerance around each site during the survey. Additionally, survey points for any given site should not overlap

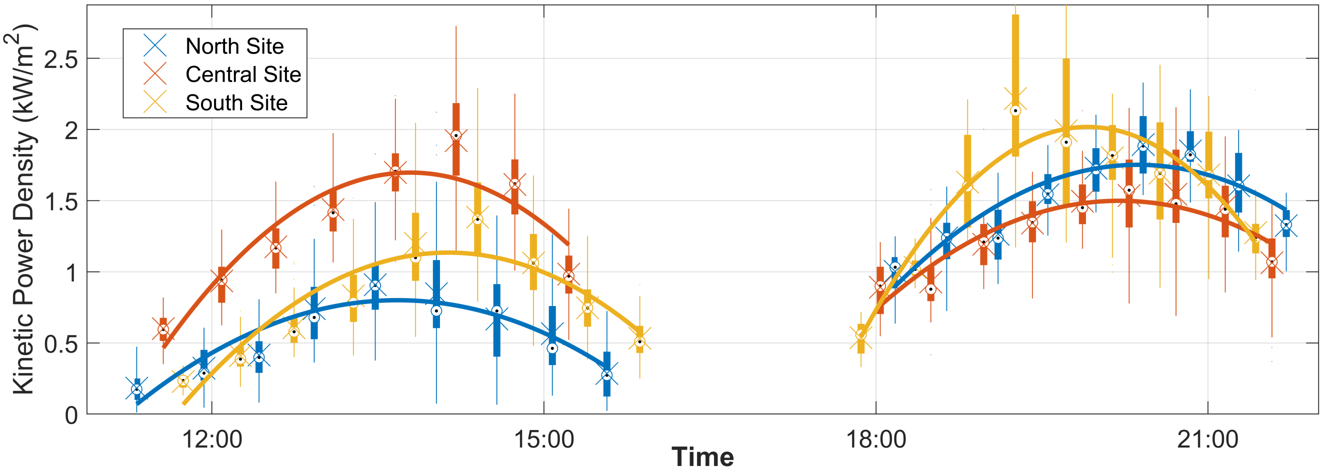

Fig. 4. Boxplots of kinetic power density at candidate sites during ebb (left) and flood (right) tides.

TABLE III
KEY MEASUREMENT STATISTICS

Site	North	Central	South
Speed, Ebb (ms^{-1})	0.97	1.34	1.11
Speed, Flood (ms^{-1})	1.42	1.34	1.41
KPD, Ebb (kWm^{-2})	0.55	1.29	0.78
KPD, Flood (kWm^{-2})	1.49	1.27	1.54
σ **Ebb** (ms^{-1})	0.17	0.08	0.11
σ **Flood** (ms^{-1})	0.06	0.09	0.11
KPD, All (kWm^{-2})	1.02	1.25	1.16

with any other, including accounting for ADCP beam spread. A summary plot showing the location of each valid 10 s measurement ensemble is shown in Fig. 5. Target tolerance was a 50 m radius around each intended site, depicted by solid rings. Average position error over continuous >5 min. measurement windows did not approach the tolerance of 50 m, as indicated in Table IV.

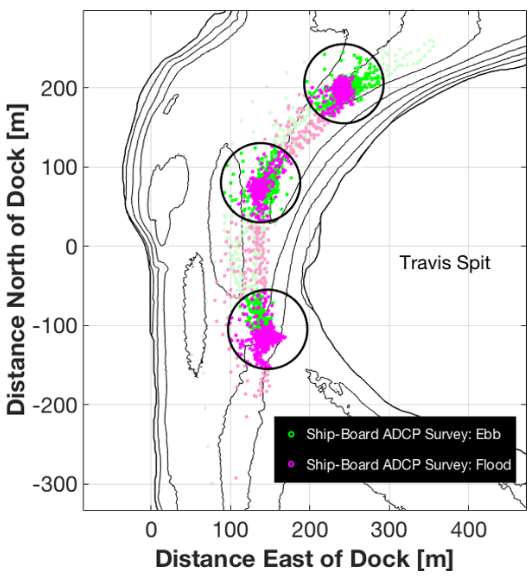

Fig. 5. Survey point locations.

Observing the ADCP's record of seabed depth over time offers additional insight into site suitability. As the vessel drifts around the target at the average distances

TABLE IV
SURVEY LOCATION ERROR

Site	Mean Position Error Ebb (m)	Mean Position Error Flood (m)
North	28	16
Central	18	16
South	16	21

reported above, variation in depth indicates sensitivity to absolute position. That is, a site with a 'flatter' depth record in time over an observation window requires lower deployment precision to land at a suitable location and maintain desired characteristics. A typical series of observations is shown in Fig. 6, starting at the North site and progressing through the Central to the South site. The North site is deepest and most uniform, followed by the Central and South in depth and uniformity, respectively, consistent with the results of the bathymetry study utilized during preliminary siting.

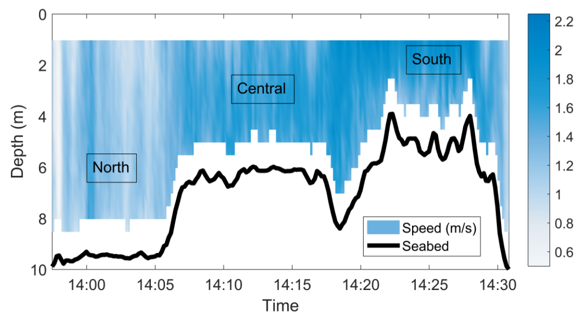

Fig. 6. Typical ADCP bottom track with velocity profile.

F. Measurement to Model Comparison

Before the vessel survey, in order to further confirm the Central site as the most suitable site for deployment, the Sequim Bay model was run at the location over the same time period to provide velocity predictions. Model results were shifted by 20 minutes to account for a post hoc calibration of boundary forcing water level. Magnitude and phase are compared in Fig.

7. Relative error was computed between model magnitude and corresponding survey points, then averaged for ebb and flood phases for results at hub-height and depth-averaged. In general, measured speeds were lower than modeled at hub-height, while peak magnitude matches well when depth-averaged. Relative error between model output and measurements are summarized in Table V.

TABLE V
MODEL & MEASUREMENT QUANTITATIVE COMPARISON

	Hub-Height	Depth-Averaged
Magnitude Rel. Error Ebb (%)	9.6	8.8
Magnitude Rel. Error Flood (%)	8.1	8.8

G. Bottom-Mounted ADCP Survey

Contributions to current at the site were determined for 29 tidal constituents using UTide. Those resulting in current ellipse magnitude greater than 0.1 m/s are reported with their associated phase in Table VI. Peak one-minute average current measured at the site was 1.8 m/s. Ebb-flood asymmetry was assessed over the period and visualized as a tidal rose in Fig 8, depicting magnitude of flow towards directions shown. Flow direction is symmetric to within 15 deg.

TABLE VI
PRIMARY HARMONIC CONSTITUENTS

Constituent	Magnitude (m/s)	Phase (deg.)
M2	0.73	16.2
K1	0.38	14.4
S2	0.30	15.8
O1	0.28	14.4
N2	0.26	15.5

V. DISCUSSION & CONCLUSIONS

The Central site was determined to be most suitable for turbine deployment. It was, on average, the most powerful and consistent site during the survey, offering the most amount of time for a turbine above cut-in speed. It maintained the highest average power despite not being the site with the highest peak currents. This point is critical, as maximum loading is a key design specification for a lander. Additionally, the Central site is closest to the shoreside point of connection, allowing for the lowest cabling costs and power losses. All three sites meet depth criteria, though the additional clearance of the Central site over the South site is a benefit. Ebb-flood assymetry at the Central site, evaluated after a longer-term survey, is low, showing the site will be suitable for the deployment of arrays of turbines taking advantage of their relative spacing.

Error and uncertainty associated with a single survey may be high. A further bottom-mounted ADCP was deployed at the site to measure flow conditions over many tidal cycles, covering a spring-neap tidal cycle. This served to refine estimates of energy production as well as better define peak conditions critical for lander design. Recorded peak speed over the longer measurement period was lower than during the survey. This highlights a benefit of conducting a short survey with finer time-resolved measurements (i.e., ability to catch instantaneous peaks) in conjunction with a more traditional survey (i.e., ability to contextualize peaks). Furthermore, the bottom-mounted ADCP record enabled tidal harmonic analysis that will provide accurate predictions of tidal currents for operations.

Preliminary site identification work utilizing FVCOM model output identified the Central site as being, on average, the most powerful - a conclusion corroborated by the vessel survey. An identified benefit of the described approach is a favorable combination of spatial and temporal resolution: the model allowed determination of favorable locations over a large area, while the single-day survey yielded critical information on instantaneous peak speeds and subtle differences between the closely-spaced sites.

The ad hoc phase shift of 20 minutes used to match the model to the data is likely related to the detailed geometry of the inlet, as well as the open boundary conditions. Phase lags are common at tidal inlets and constrictions, where frictional effects can be significant. Future work may be able to isolate the relative importance of local friction versus boundary conditions in setting the phase lag of the inlet.

Despite uncertainty, the results of this modeling and survey effort strongly indicate the Central site is the most suitable of the three studied. It is not, nor is it intended to be, an optimal location for a commercial deployment of a tidal turbine; it is believed to be an excellent location to study deployment, operation and maintenance of a kilowatt-scale device.

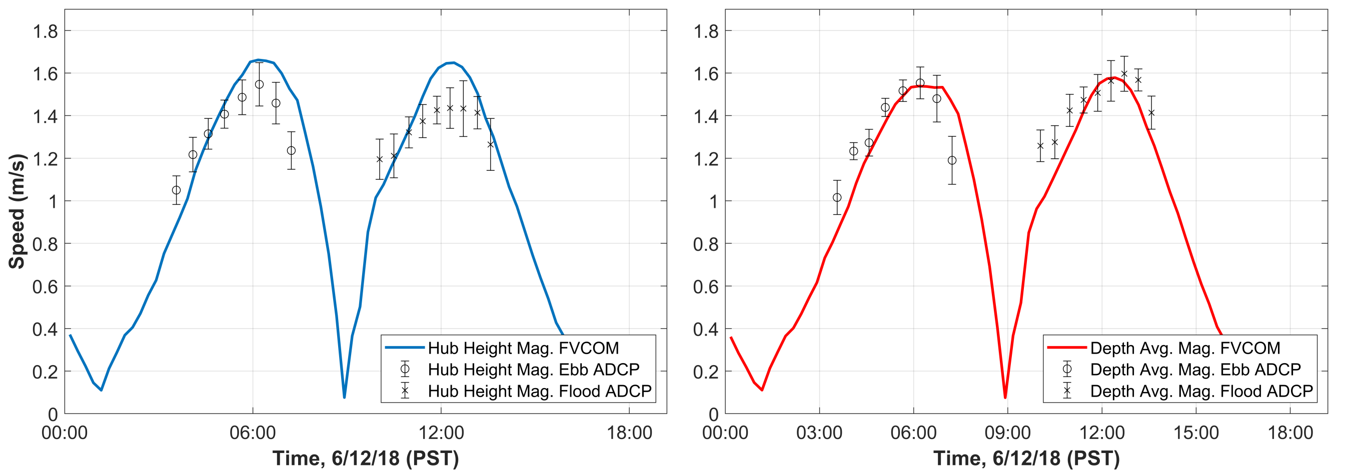

Fig. 7. Comparison of speed magnitude at hub height (left) and averaged over depth (right).

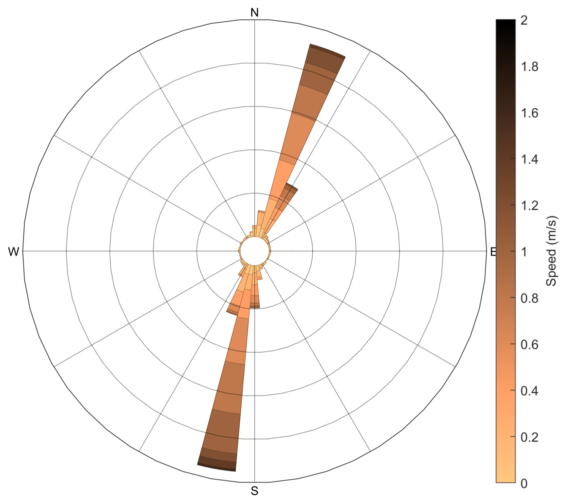

Fig. 8. Flow speed and direction at Central site from bottom-mounted ADCP.

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