Idealized Headland Simulation for Tidal Hydrokinetic Turbine Siting Metrics

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***Abstract*— Tidal hydrokinetic energy is a renewable energy source that is currently being researched at the University of Washington. Admiralty Inlet, an area of interest for pilot- and commercial-scale tidal hydrokinetic turbine placement, has a prominent headland that significantly affects the tidal flow and, therefore, potential turbine siting. A numerical model has been created using the Regional Ocean Modeling System to simulate an idealized, three-dimensional rectangular channel with a symmetric headland. Results from this simulation are examined using several metrics put forth by the European Marine Energy Council for characterizing potential tidal hydrokinetic energy sites. Areas of high mean kinetic density and various measures of asymmetry of tidal flow that may be relevant for turbine developers are highlighted.**

I. Introduction

Tidal hydrokinetic energy is a potentially viable resource for clean, predictable, and renewable energy in the Puget Sound area of western Washington state. As such, University of Washington researchers have been working to understand the complex issues surrounding the field as part of the Northwest National Marine Renewable Energy Center (NNMREC), a group funded by the Department of Energy to study tidal energy. NNMREC partner Oregon State University focuses their efforts on wave energy [1].

The Puget Sound is a deep, fjord-like estuary with several large cities, including Seattle and Tacoma, on its shoreline (Fig. 1). The Sound supports about 3.5 million people [2], a much higher population density than on the eastern half of the state, where much of the existing (conventional hydroelectric and wind) electricity is produced. One attraction of tidal hydrokinetic energy for this region is its proximity to a large population and thus shorter transmission lines. Another attraction is that, unlike wind and wave energy, tidal hydrokinetic energy is a highly predictable source of electricity and would be produced regardless of weather factors that may affect energy consumption and production of other sources of renewable energy.

One of the most promising locations for a commercial-scale tidal turbine array is in Admiralty Inlet, the main entrance to the Puget Sound (Fig. 1) [3] [4]. Admiralty Inlet has depths between 50 and 85 meters and currents up to 3 m/s. These factors, along with the large area of the region, make

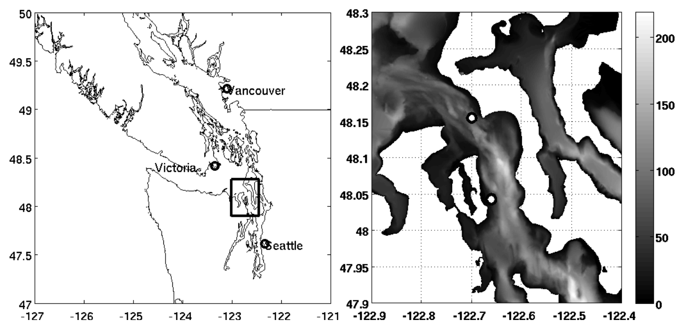

Fig. 1. The left shows a coastline map of northwestern Washington State, part of Vancouver Island and Vancouver, B.C. The black box in the Puget Sound shows the area of interest, Admiralty Inlet, which is plotted on the right with bathymetry as shading. Lighter gray represents deeper water and two white circles show the approximate location of two pilot tidal hydrokinetic turbine projects currently being pursued.

Admiralty Inlet a strong candidate for tidal hydrokinetic power development. This is also an area for two potential pilot-scale test sites: one near Admiralty Head (upper white circle in Fig. 1) being developed by the Snohomish Public Utilities District in an effort to fulfill their obligation of 15% of their energy production from new renewable sources by 2020 [5], and one off Marrowstone Island (lower white circle in Fig. 1) being developed by the Navy to work toward the National Defense Authorization Act of 2007 requiring 25% renewable power by 2025 [6].

The bathymetry in Admiralty Inlet is variable with steep sidewalls and, most significantly, a double sill with a deep trough in between. This dynamic flow region includes the possible presence of internal waves and internal hydraulic jumps produced by the sills [7]. In addition, flow is compressed inward due to two headlands along the channel, one on each side. The larger of the two is Admiralty Head on the east side of the channel. Eddies are known to be generated during each flow direction through the tidal cycle [8]. The vortices may travel downstream or across the channel with varying speeds, and may persist for more than one tidal cycle. The influence of these bathymetric and coastline features on the utility of any given location in Admiralty Inlet for tidal hydrokinetic energy is necessary to know before placing a significant number of turbines. It is desirable to quantify what flow conditions create the "best" turbine site. For this paper, we will focus on the influence a single prominent headland in a channel, similar to that of Admiralty Inlet, has on potential turbine sites in the channel, as measured by a series of metrics.

In order to facilitate the study of tidal energy sites around the world with different bathymetry, coastline features, currents, and stratifications, a series of metrics have been proposed by the European Marine Energy Centre (EMEC) [9]. Rather than attempt to characterize and track the wide variety of features that may exist at any of these sites, these metrics quantify their influence on a potential turbine in that location. In this way, the effect of the features is felt indirectly, but is measured in a quantifiable way that may be then be passed on to interested parties. Turbine developers may want to know existing conditions in sites that could support development, and utilities will need to be able to locate these desirable locations.

The first section in this paper will explain the metrics used to evaluate these simulation results. Next, the numerical model will be explained in detail. Results will be shown and explained, followed by discussion and conclusions and future work.

II. Metrics

Metrics proposed by EMEC to scientifically and consistently evaluate potential tidal hydrokinetic energy sites include measures of vertical shear, turbulent eddy intensity, asymmetry of currents on ebb versus flood, peak sustained velocities, velocity distribution and mean kinetic power density over a tidal cycle [9]. This study follows previous analysis of Acoustic Doppler Current Profiler (ADCP) data from Admiralty Inlet in terms of turbine siting metrics [10]. We will focus on two of these metrics: kinetic power density and asymmetry of flow. These metrics may be considered in an idealized headland numerical model in order to characterize the effects that a headland in realistic situations may have on tidal site development. Other metrics proposed by EMEC are more in-depth (*e.g.* turbulent eddy intensity) or would be more suited for an idealized model of bathymetric features that are expected to have vertical structure (*e.g.* vertical shear) in order to isolate the effects and more fully understand them.

This research builds on work that has already been completed on site characterization in the Puget Sound [3] [4] [10]. Previous work has already identified areas of strong currents, leading to Admiralty Inlet's consideration for development [3] [4]. Other work used many of the metrics to analyze ADCP data that has been collected in Puget Sound [10]. Field data gives temporal resolution, but it is more difficult to obtain spatial resolution (though there has been work in this area [10] [11]). A numerical model gives both temporal and spatial information. With this model, questions can be answered in more locations using less money.

Some tidal hydrokinetic turbine designs assume the flow is bidirectional, *i.e.* $180°$ between flood and ebb. These designs may not fair well in a location where the currents significantly deviate from bidirectionality. Other turbine designs have yaw that allow for the face of the turbine to follow the flow to a certain extent. Such a design would be more appropriate for asymmetric flow locations. Tightly tied into this is how spread out the flow is in each tidal direction. Also, for a commercial-scale array of tidal hydrokinetic turbines, it will be important to know how the power will be generated throughout a day. For an area like the Puget Sound, which has mixed, mainly semi-diurnal tides, there will be two peak flood tides and two peak ebb tides per day. The power generation asymmetry parameter P_M discussed in Section II-B.3 represents whether this power production would be stronger during one tidal direction or not. At the limits, we find that $P_M = 0$ is the ideal situation for even power production and $P_M = 1$ is the case where power is produced exclusively in one tidal direction.

In its guidelines, EMEC states that analysis should be done at either an assumed hub height or should use depth-averaged flow information. In this paper, all flows have been depth-averaged for analysis.

A. Mean Kinetic Power Generation

The primary requirement of a tidal hydrokinetic energy site is strong enough currents to produce a viable amount of power. This can be quantified by calculation of the mean kinetic power density. Without a resource to take advantage of, there is no need to look into further detail about the site.

Kinetic power density is calculated as

$$K(t) = \frac{1}{2}\rho s^3, \tag{1}$$

where ρ is the depth-averaged density at the location and s is the speed calculated from the east-west (u) and north-south (v) velocities, such that $s = \sqrt{u^2 + v^2}$. The mean kinetic power density is then found by averaging kinetic power density over one tidal cycle:

$$K_M = \frac{1}{T}\int K(t)dt, \tag{2}$$

where T is the period of one tidal cycle. A kinetic power density of 1 kW/m^2 and higher is considered economically viable [12]

B. Asymmetry of Flow

The asymmetry of flow can be characterized using several measures: bidirectionality, the "spread" of directions on each flood and ebb, and the strength of power generation on ebb versus flood tides.

1) Bidirectionality: Bidirectionality of tidal flow at an (x, y) point can be measured by finding the mean direction of flow on ebb and on flood tide, then finding the difference. In order to accomplish this, first a principal axis decomposition is used to split the flow at each point into ebb and flood information [13]. Next, we find the angle of each (u, v) model output point, and calculate the mean of the ebb and flood angles separately. Note that outputs for which $s < 0.5$ m/s are discarded in the calculation of mean angle and

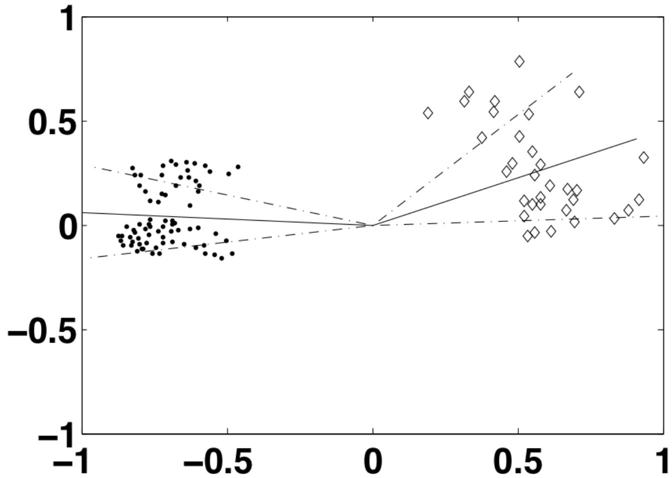

Fig. 2. v-velocity vs. u-velocity (m/s) at one (x, y) point, with ebb currents shown as black dots and flood currents shown as outlined diamonds, after principal axis decomposition. The solid black line shows the mean angle for each direction and the dotted lines show the standard deviation on each side of the mean angle. The closer together the lines are, the less spread out the flow is in that direction.

standard deviation from mean angle, since power would not be generated at these times and including them in the calculation would falsely skew the results [10]. The asymmetry parameter can then be calculated as [10]:

$$a = |\theta_{ebb} - \theta_{flood} - 180°|. \quad (3)$$

From this definition, if a flow is perfectly bidirectional, $a = 0$.

2) Spread in Tide Direction: Closely linked to the bidirectionality parameter a is the spread in direction at each point. After calculating the mean angle for each (x, y) point on ebb and flood, we can also calculate the standard deviation of that mean angle, $\theta_{std,ebb}$ and $\theta_{std,flood}$, giving us another measure of bidirectionality throughout a tidal direction. Because the size of θ_{std} is due to the headland and will be largest on the lee side of the headland, and due to the symmetry of the problem, we have taken the maximum value between ebb and flood at each point and used that to represent the spread throughout the domain.

These first two parameters are illustrated together in Fig. 2, an example of the analysis at a single point.

3) Power Generation Asymmetry: A third measure of asymmetry of tidal direction is how much more power would be generated on flood versus ebb or vice versa. This is calculated by once again first splitting the velocities into ebb and flood currents. Mean kinetic power density is calculated, as in Section II-A, for each direction for comparison. Then a ratio is formed between the two as follows:

$$P_M = 1 - \frac{min(K_{M,ebb}, K_{M,flood})}{max(K_{M,ebb}, K_{M,flood})}. \quad (4)$$

P_M is a measure of the deviation from equal power production. As P_M approaches 0, power would be produced more evenly throughout the day at that location. As P_M approaches 1, the power production at that location becomes more biased toward one tide direction or the other. We take the absolute value of P_M for visualization.

III. Model

The Regional Ocean Modeling System (ROMS) [14] [15], a three-dimensional hydrostatic model with terrain-following vertical coordinates and structured horizontal coordinates, was employed to examine the effect of a symmetric headland on the tidal hydrokinetic siting characteristics of a flat-bottomed rectangular channel.

The model domain is 105 km long and 7 km wide with a flat bottom of depth 157 meters. There are open boundaries at the west and east ends, and walls at the north and south ends. The headland is symmetric and about 5 km across and extends just over 2 km into the channel. An M_2 tide is forced on both open boundaries with a phase difference approximated using the shallow wave speed, distance, and frequency of forcing. Both free surface and u-velocity are forced using the ROMS flags `FSCHAPMAN` and `M2FLATHER`. The initial density is forced at the east and west open boundaries, and baroclinic momentum is radiated out of the system using open boundary flag `M3RADIATION`. Maximum speed reaches about 2.5 m/s and the density field is initialized using a linear stratification from 1025 kg/m^3 at the bottom to 1023 kg/m^3 at the surface. This model domain is meant to simulate bulk parameters of flow through Admiralty Inlet.

The model was run for five tidal cycles and was ramped up over part of the first cycle. Averages over a tidal cycle were taken from the last tidal cycle of the simulation, and tidal asymmetry was analyzed over the final four tidal cycles.

IV. Results

Plots of results show a portion of the domain surrounding the headland, and the plots are nearly symmetric due to the symmetry in the problem of the channel and the headland. The results are not perfectly symmetric. We suspect this is due to a combination of the facts that the channel is not exactly the same length on either side of the headland and that the boundary forcing is not perfectly radiative to outgoing waves. The Coriolis force is included in the dynamics as well.

Fig. 3 shows the amplification of speed due to the presence of the headland. The incoming far-field speed is increased by a factor of two around the headland. This is similarly reflected in Fig. 4, where the mean kinetic power density, $K_M(x, y)$ divided by the far field K_M value, is shown. As we might expect, the area of highest mean kinetic power density is off the tip of the headland where the headland acts to speed up the flow significantly. It is worth noting that the amplification in K_M is much higher than in mean speed since $K_M \propto s^3$ and a small increase in speed leads to a large increase in power.

Fig. 5 shows the vorticity at four snapshots through a tidal cycle: peak flood, slack water, peak ebb, and slack water. We see that eddies are generated in each direction and persist after the flow changes direction, similar to case 2 examined in a previous headland study by Signell and Geyer [16]. We

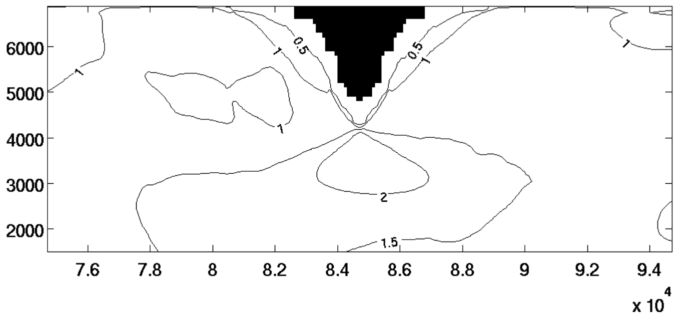

Fig. 3. The mean speed over a tidal cycle divided by the nominal far field speed is shown as contours from a top-down view. The headland is shown in black and x and y axes are in meters. This shows the amplification of speed induced by the presence of the headland.

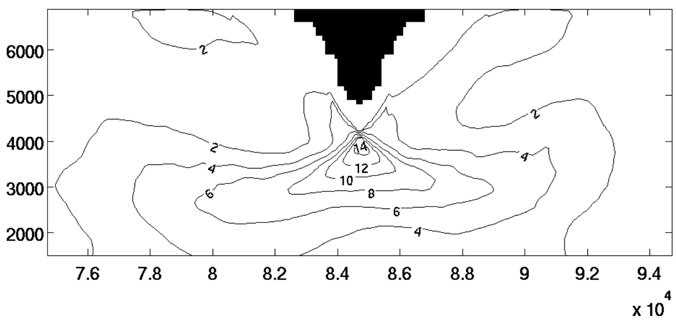

Fig. 4. The mean kinetic power density K_M divided by the nominal far field K_M is shown as contours from a top-down view. The headland is shown in black and x and y axes are in meters. The area of highest K_M amplification is off the tip of the headland.

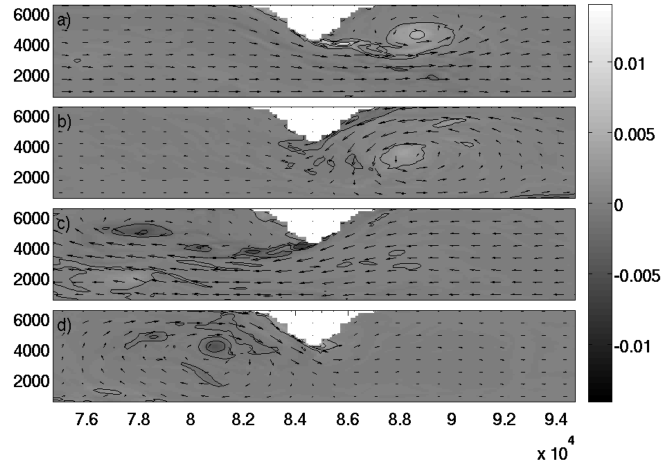

Fig. 5. Vorticity is shown in gray shading with overlaid velocity vectors from a top-down view. The headland is shown in black and x and y axes are in meters. Subplot a). shows the vorticity near peak flood, b.) near slack water, c.) near peak ebb, and d.) near slack water. Eddies are generated in both tidal directions and persist beyond each flow direction.

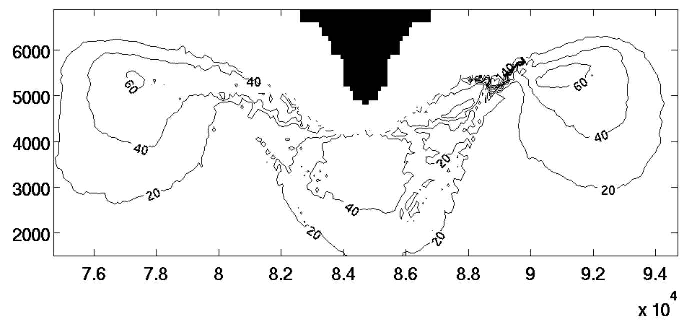

Fig. 6. The bidirectionality parameter a is shown as contours from a top-down view. The headland is shown in black and x and y axes are in meters. The most bidirectional flows, where a is smallest, are in front of and to the side of the tip of the headland.

also find that the eddies tend to fill the entire channel cross-section. Given the eddy field and context of tidal flow around a headland, we can understand the flow asymmetry parameters.

In Fig. 6, we see that the most bidirectional area is diagonal to each side of the headland tip. The least bidirectional areas correspond to the areas of Fig. 5 where the eddy currents are perpendicular to the expected along-channel flow direction.

Note that the area right around the headland is empty despite presumably having the highest asymmetry parameters because the flow there is too slow to produce power.

The spread parameter θ_{std}, in Fig. 7, shows the fact that on, for example, flood, the flow west of the headland will be along-channel and east of the headland will be affected by the headland. On ebb, then, the situation is reversed. The resultant pattern is the contoured area to either side of the headland from the currents spreading after being compressed by the headland. This asymmetry is due to the vortices being formed by flow separation on the lee side of the headland.

The power generation ratio P_M, shown in Fig. 8, is close to zero off the tip of the headland, since on both flood and ebb tides the currents are increased at that location. However, we also see an interesting reach out to the sides and away from the headland where $P_M \approx 0$. More expected behavior is seen diagonally off from the headland tip, where $P_M \approx 1$ and power production would be much higher on one tidal direction over the other. This again can be attributed to the vortices being shed by the headland which sped up the flow on the lee side.

Figs. 9, 10, and 11 show K_M in the background as shades of gray with contours of the asymmetry parameters overlaid as contours for comparison. Midrange values of a coincides with high values of K_M, but the highest values of a are closer to the headland in undesirable locations, judging by K_M values (Fig. 9). Low values of θ_{std} coincide with high values of K_M (Fig. 10). Right off the headland tip, in the area of high K_M is also an area of low P_M, though with increasing distance from the headland comes lower K_M and higher P_M (Fig. 11).

Overall, we find that the area off the headland tip corresponds to the area of highest K_M, lowest θ_{std}, low P_M and mid-range a.

V. Discussion

Gathering information about metrics is an important first step for charting and understanding the flow in a development area of interest. However, deciding where to place turbines

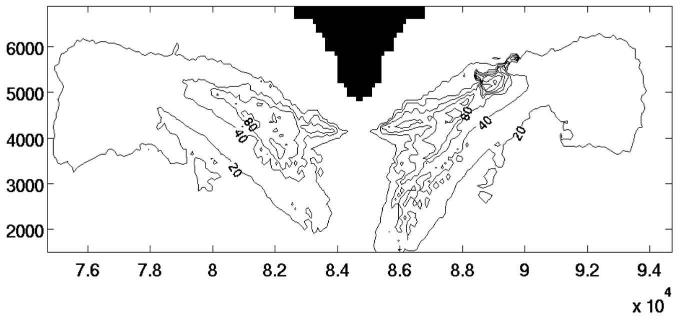

Fig. 7. The spread parameter θ_{std} is shown as contours from a top-down view. The headland is shown in black and x and y axes are in meters. The least spread out flows, where θ_{std} is smallest, are off the tip of the headland.

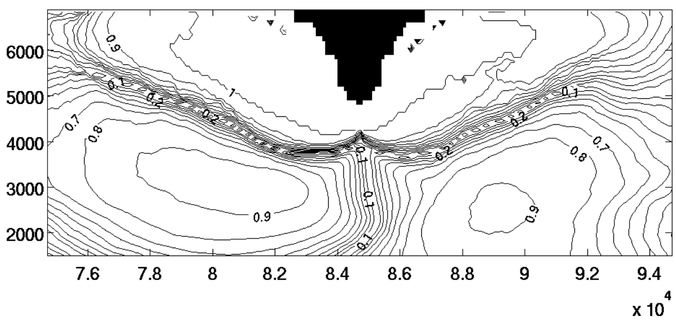

Fig. 8. The power generation asymmetry parameter P_M is shown as contours from a top-down view. The headland is shown in black and x and y axes are in meters. $P_M \approx 0$ off the tip of the headland as well as to the sides and away from the tip, whereas $P_M \approx 1$ diagonally to the sides from the headland tip.

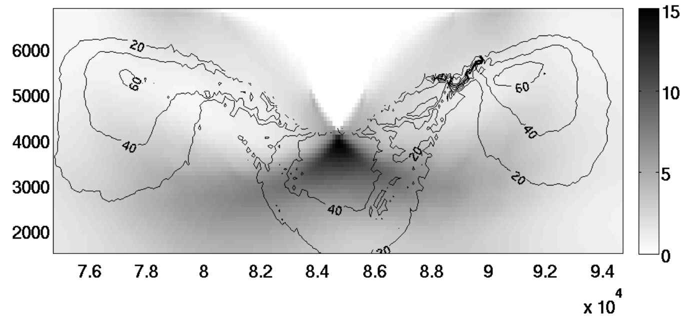

Fig. 9. K_M as shades of gray with a overlaid as contours from a top-down view. The headland is shown in white and x and y axes are in meters. Areas of moderate asymmetry (20° up to 40° off) coincide with areas of high K_M, while the highest asymmetry values are in less desirable areas of low K_M.

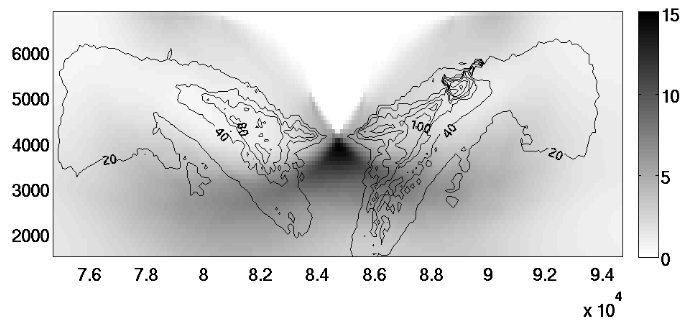

Fig. 10. K_M as shades of gray with θ_{std} overlaid as contours from a top-down view. The headland is shown in white and x and y axes are in meters. Areas of highest K_M tend to be where θ_{std} is lowest.

using this information is another step altogether. There are many ways to understand the information laid out in this paper, depending on the realistic situation. For example, Fig. 4 shows a small area of dramatically high mean kinetic power density off the tip of the headland, compared to the nominal channel mean kinetic power density. The same area, though, is more asymmetric through a tidal cycle than other, less power-dense areas. This could imply multiple courses of action. On one hand, if the far-field K_M value is too low to be commercially viable for power generation, it may be worth choosing a turbine design that can handle a less bidirectional flow so that it may be placed in the peak power area. On the other hand, if even the far-field K_M is large enough for economic turbine placement, it would make more sense to use the plots as a guide for areas to avoid due to asymmetry, and the area of peak K_M may not be worth the stress on a turbine placed in that location. Any decision-making based on data or model analysis using siting metrics will always be site and situation specific.

In the former case in which there is a small region of sufficiently strong currents for development, a commercial-scale array may not be a realistic option. Moreover, there is the possibility of flow redirection anytime flow is partially blocked [17]. This would not be as much of a problem in the case with appreciable kinetic power density throughout the channel, but in a scenario with a limited region, turbine presence could alter the channel velocity field.

VI. Conclusions and Future Work

This paper has examined a few of the metrics outlined by EMEC for assessing potential tidal energy sites using an idealized numerical model of a rectangular channel with a symmetric headland near the center of the channel.

We find that the area of highest mean kinetic power density, K_M, is off the tip of the headland. This area also has low spread of direction on each tide and a low power generation ratio, meaning that power production would be even throughout the day. However, the currents at this area are not particularly bidirectional, which could present a problem for some turbine designs if accessing the peak kinetic power density region.

Future work in this headland study could involve evaluating a wider variety of siting metrics and considering the vertical structure of the metrics. Additionally, comparison with field data analysis is an important step to pursue, even for idealized simulations. A follow-up question to this work is: given the spatial structure of these parameters, what would be the best arrangement for a turbine array? This would be, in other words, a study of turbine placement in terms of optimization of site characteristics. Future work could also examine dependence of these and other metrics on a parametrized headland, looking at the effects of changing headland size and shape and forced velocities to siting considerations. This work would

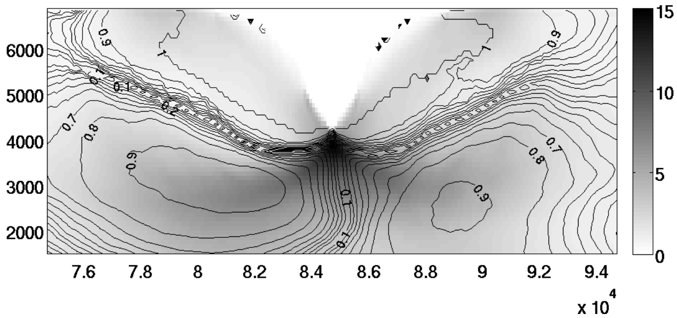

Fig. 11. K_M as shades of gray with P_M overlaid as contours from a top-down view. The headland is shown in white and x and y axes are in meters. The peak K_M values coincide with areas where $P_M \approx 0$, right off the headland tip, but further from the tip, as K_M decreases, P_M increases.

be generalized and potentially useful for quickly narrowing the selection of tidal sites worthy of spending money on gathering field data and more realistic modeling. Additionally, simulation output from all of these potential headland studies could be analyzed to optimize siting for power extraction [18].

Similar work could be accomplished for idealized sill configurations to look at EMEC metrics as well as power extraction optimization.

Future plans include many of these ideas as well as a realistic model of Admiralty Inlet to examine all relevant metrics in a more specific and realistic setting. This is attractive because it will give much more specific information for siting in this location, but will be less generalizable to other potential locations.

Perhaps most importantly, as this analysis is completed, it will have to be synthesized in order to understand its implications for turbine siting, particularly large-scale commercial siting. This will require input from many groups, including device developers and utilities who are looking to build arrays in the future.

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