Rich Passage Tidal Energy Resource Characterization

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Abstract

Current and wave measurements were taken in Rich Passage in Puget Sound, WA, during fall 2014. Two instruments were deployed at the west end of Rich Passage; one measured currents and the other measured both currents and waves. The main objectives of the study were to measure waves generated by vessels transiting Rich Passage and to quantify the tidal energy resource of the channel. This report presents the analysis of the measured currents and an assessment of the hydrokinetic power available in Rich Passage.

1 Site Description

Rich Passage is a tidal channel south of Bainbridge Island in Puget Sound, WA (47.5867° N, −122.5424° W), between the island and the Kitsap Peninsula (Figure 1). Washington State Department of Transportation ferries transit Rich Passage on routes connecting Seattle to Bremerton. At its west end, the channel is approximately 28 m deep and 550 m wide; it is oriented approximately 45° from north in the clockwise direction, and it is expected that the flow has a similar principal direction.

2 Data Collection

Tidal currents and waves were measured at Rich Passage, WA, continuously from 15 September to 18 November 2014. Two Sea Spiders (SS02 and SS04; Figure 2) were deployed at the west end of Rich Passage (Figure 3). SS02 was equipped with a Nortek Continental ADCP to measure currents every minute throughout its deployment; SS04 was equipped with a Nortek Acoustic Wave and Current Profiler (AWAC) to measure currents and waves (Table 1). SS02, deployed near the center of the channel, measured the strongest currents in Rich Passage, while SS04, deployed at the north end of the channel, measured the waves generated mainly by ferry wakes.

A cross-channel section of velocity profiles and seven conductivity, temperature, depth (CTD) profiles were taken in Rich Passage. The section from north to south between the Sea Spider 002 and 004 locations (Figure 3) was conducted on 16 September 2014 at 09:06 local time on the flood tide (Figure 4). Velocity was measured by a downward-looking RDI ADCP mounted aboard the R/V *Jack Robertson*.

CTD profiles were taken at seven locations across the west end of Rich Passage on 16 September 2014 between 08:15 and 09:15 local time on the flood tide (Figure 5). From these profiles, we conclude that the flow in Rich Passage is well mixed.

3 Analysis of Velocity Measurements

ADCP velocity measurements from SS02 and SS04 are analyzed to characterize the tidal energy resource at Rich Passage. Only current measurements, and no wave measurements, collected by the Nortek AWAC on SS04 are used in this analysis. A different approach was used to process data from the AWAC because there were no current measurements taken when the instrument was measuring waves.

3.1 Raw Measurements

All data were processed with Matlab. Low beam amplitude measurements (< 50), surface bins measurements, and velocity spikes where removed from the data and not used in this analysis. Time series of east, north, and vertical velocity profiles as well as free surface elevation from SS02 and SS04 show spring and neap tides clearly (Figures 6 and 7). A semi-diurnal inequality in horizontal velocities and free surface elevation was observed between the two ebb and the two flood currents occurring each lunar day.

Plotting currents observed at both locations 10 m above the sea bottom (Figure 8) shows differences in current magnitude and direction at the Sea Spider sites. SS02, within the channel, had currents constrained to a principal direction. SS04, at the west end of the channel, had highly scattered currents and no clear principal axis.

3.2 Harmonic Analysis

Harmonic analysis of horizontal tidal currents measured about 10 m above the sea bottom (Table 2) was performed using UTide (*Codiga* 2011), a unified tidal analysis and prediction model that accommodates two-dimensional time series with irregular sample times. From this analysis, 35 tidal constituents with a signal to noise ratio (SNR) greater than 2 are recognized. The most energetic from both data sets are the M_2 (77%), K_1 (9%), S_2 (6%), O_1(3%) and N_2(2%). Figures 9 and 10 plot the tidal ellipses constructed from data collected at the SS02 and SS04 sites.

3.3 Tidal Energy Resource Characterization

The methods developed by *Polagye and Thomson* (2013) are used to characterize the tidal energy resource at Rich Passage. A set of Matlab codes for this purpose is available at the Pacific Marine Energy Center website.[1]

Because the vertical velocities at SS02 and SS04 are relatively small compared to horizontal velocities, the tidal energy is characterized in terms of the horizontal velocity, which is defined as follows (*Polagye and Thomson* 2013),

$$U_h = \pm\sqrt{u^2 + v^2} \tag{1}$$

where u and v represent the east and north velocity components, respectively. The plus and minus signs define flood and ebb tides, respectively. Currents are analyzed

[1] http://depts.washington.edu/nnmrec/characterization

as a whole, and separately as ebb and flood currents. The method uses principal component analysis to define the flood and ebb principal axes. The time-averaged metrics used to study the tidal energy resource are mean speed, mean power density, ebb/flood speed asymmetry, principal direction, ebb/flood direction asymmetry, and direction deviation (Table 3). Further details of these metrics and methods are available in *Polagye and Thomson* (2013). Vertical profiles of these time-averaged metrics are presented in Figures 11 and 12. Flood tide is from the northeast to the southwest within Rich Passage.

4 References

Codiga, D., "Unified tidal analysis and prediction using the UTide Matlab functions." *Technical Report 2011-01,* Graduate School of Oceanography, University of Rhode Island, Narragansett, RI, 2011.

Polagye, B., and J. Thomson, "Tidal energy resource characterization: Methodology and field study in Admiralty Inlet, Puget Sound, USA." *Proc., Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, **227**: 352-367, 2013.

5 Tables

Table 1: Sea Spider deployment locations and sampling parameters.

Sea Spider	**SS02**	**SS04**
Instrument	Nortek Continental	Nortek AWAC
Frequency (kHz)	470	1000
Lat	47.5887°	47.5892°
Lon	–122.5641°	–122.5681°
Depth (m)	28	24
Time (days)	60	60
Sampling Frequency	1 min	1 min (42 min of every hour)
Δz (m)	1	1

Table 2: Harmonic analysis results for the most energetic tidal constituents measured about 10 m above the sea bottom at two locations in Rich Passage.

Sea Spider	**SS02**				**SS04**			
Instrument	Nortek Continental				Nortek AWAC			
z (m)	10				10.09			
Tidal Constituent	Major Axis (m)	Minor Axis (m)	Ellipse Orientation (°)	Phase (°)	Major Axis (m)	Minor Axis (m)	Ellipse Orientation (°)	Phase (°)
M_2	0.981	0.0209	44.1	117	0.557	0.0607	29.3	117
K_1	0.341	0.0184	44.3	4	0.182	0.0054	38.4	7
S_2	0.280	0.0072	43.6	134	0.152	0.0164	31.7	129
O_1	0.190	0.0224	45.4	2	0.101	0.0072	40.9	352
N_2	0.181	0.0025	44.8	76	0.103	0.0269	29.8	72

Table 3: Time-averaged metrics for tidal energy assessment in Rich Passage.

Site		Rich Passage	
Location		SS02	SS04
All	Velocity:		
	Mean Speed (m/s)	0.69	0.45
	Max. Speed (m/s)	1.98	1.61
	Ebb/flood asymmetry	0.86	1.40
	Power:		
	Mean power density (kW/m^2)	0.34	0.09
	Ebb/flood asymmetry	0.62	3.31
	Direction:		
	Principal axis (°)	225.87	242.19
	Ebb/flood asymmetry (°)	10.81	18.18
Flood	Velocity:		
	Mean Speed (m/s)	0.74	0.37
	Max. Speed (m/s)	1.98	0.97
	Vertical Shear (m/s/m)	0.019	0.016
	Power:		
	Mean power density (kW/m^2)	0.42	0.04
	Direction:		
	Principal axis (°)	50.92	70.41
	Standard deviation (°)	4.45	12.98
Ebb	Velocity:		
	Mean Speed (m/s)	0.64	0.52
	Max. Speed (m/s)	1.65	1.61
	Vertical Shear (m/s/m)	0.024	0.025
	Power:		
	Mean power density (kW/m^2)	0.26	0.15
	Direction:		
	Principal axis (°)	220.11	232.22
	Standard deviation (°)	4.34	18.84

6 Figures

Figure 1: Rich Passage in Puget Sound, WA (from Google Earth©).

Figure 2: Sea Spiders aboard R/V *Jack Robertson* before deployment in Rich Passage.

Figure 3: Sea Spider locations in Rich Passage and a cross-channel transect (red line) (from Google Earth©).

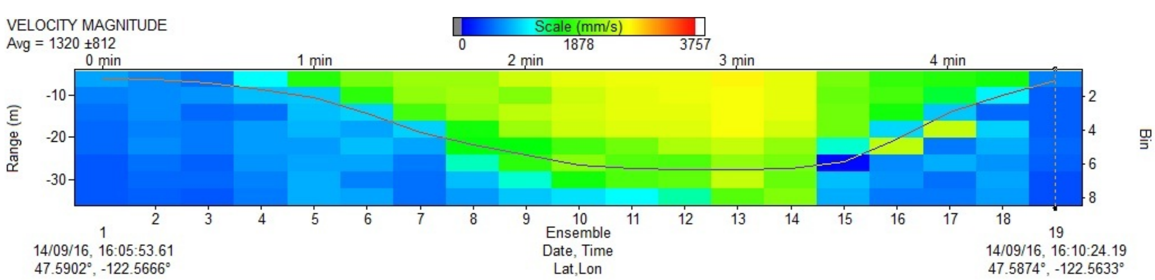

Figure 4: Velocity magnitude along a cross-channel section of Rich Passage from vessel-mounted, downward-looking ADCP measurements.

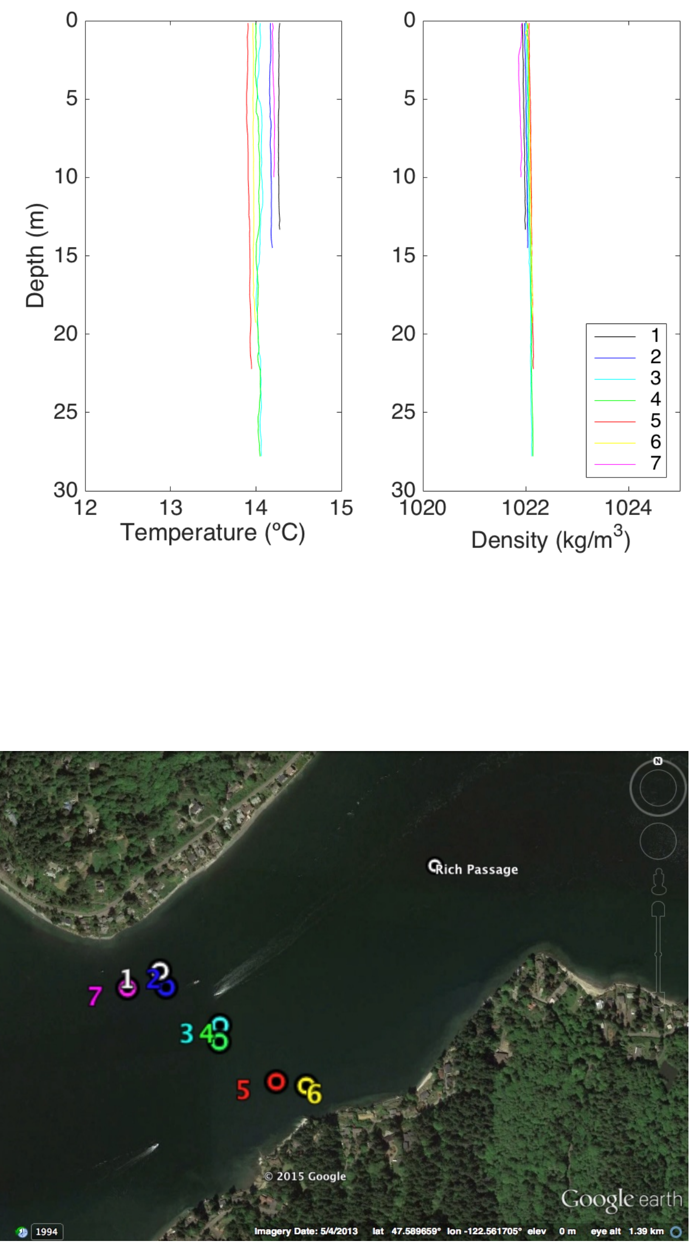

Figure 5: Vertical CTD profiles of (upper) temperature (°C) and density (Kg/m^3) at (lower) seven locations in Rich Passage (from Google Earth©).

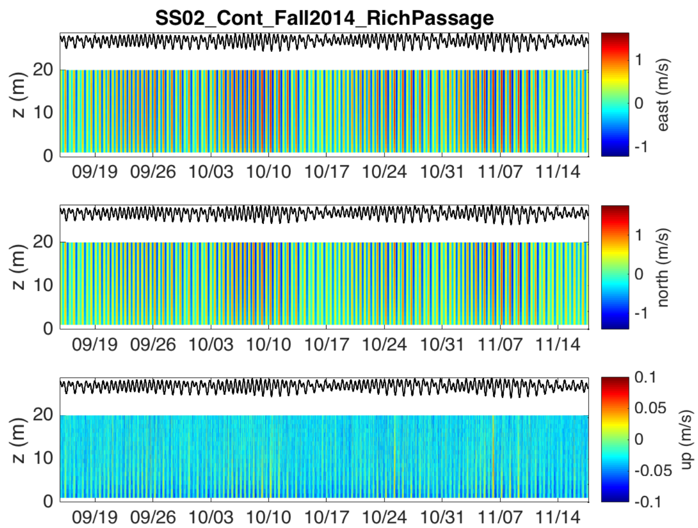

Figure 6: Time series of free-surface and velocity profiles observed at SS02.

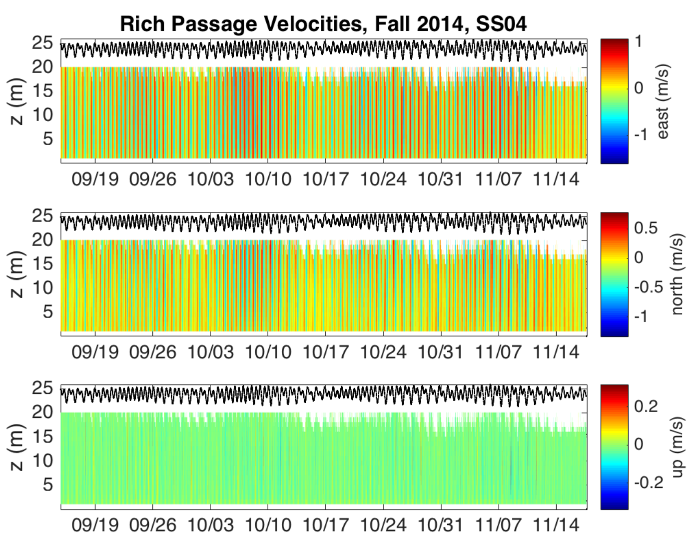

Figure 7: Time series of free-surface and velocity profiles observed at SS04.

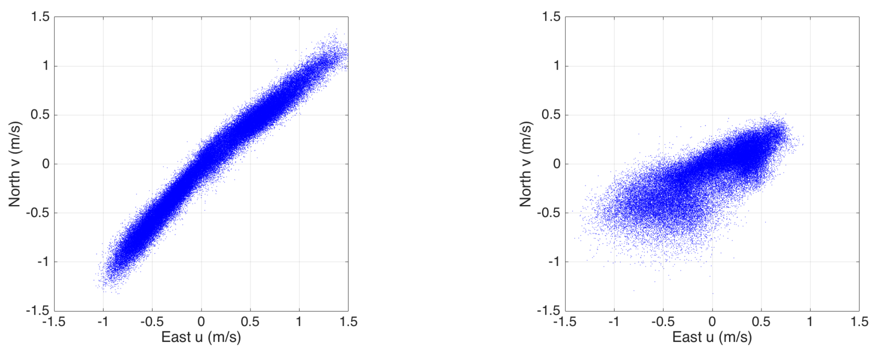

Figure 8: Velocity component measurements about 10 m above the sea bottom at SS02 and SS04.

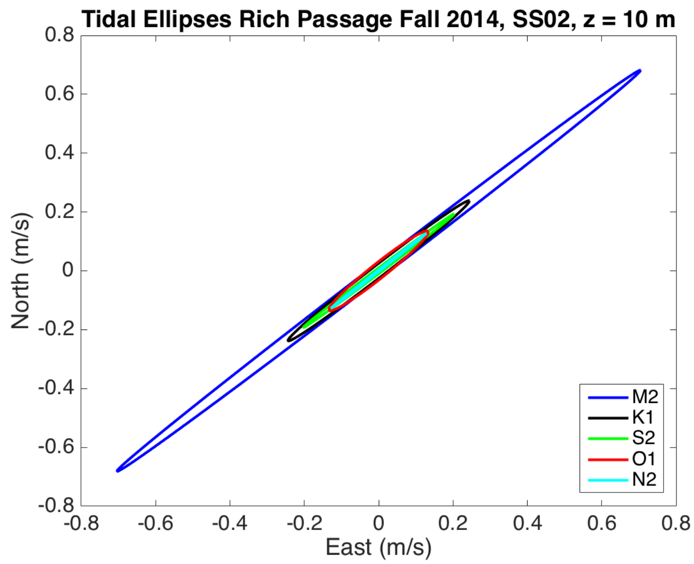

Figure 9: Tidal constituents ellipses for currents measured 10 m above the sea bottom at SS02.

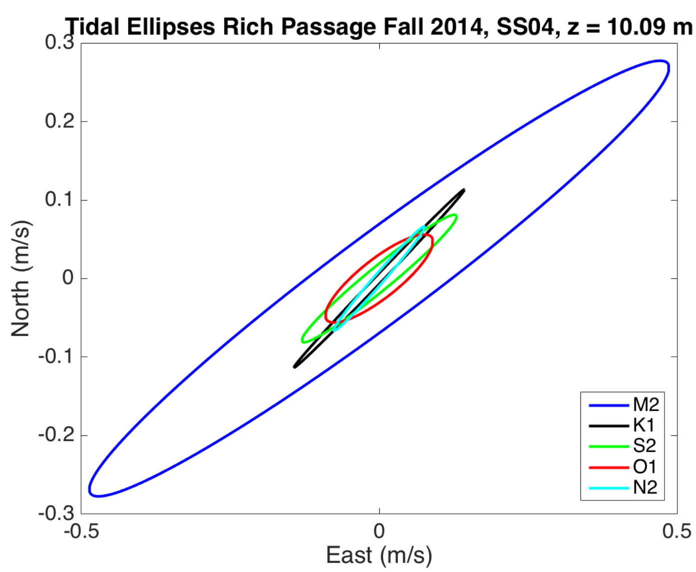

Figure 10: Tidal constituents ellipses for currents measured about 10 m above the sea bottom at SS04.

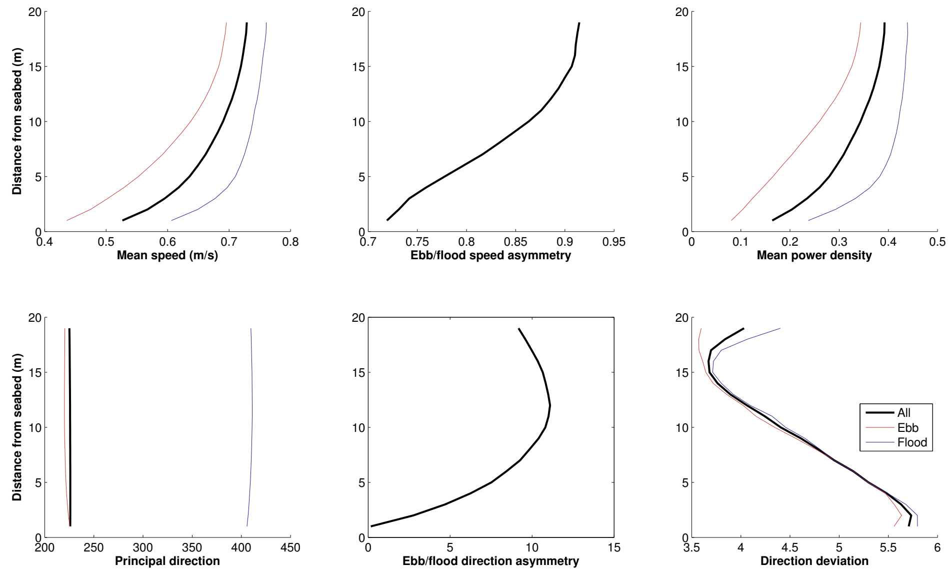

Figure 11: Vertical profile metrics at SS02 in Rich Passage.

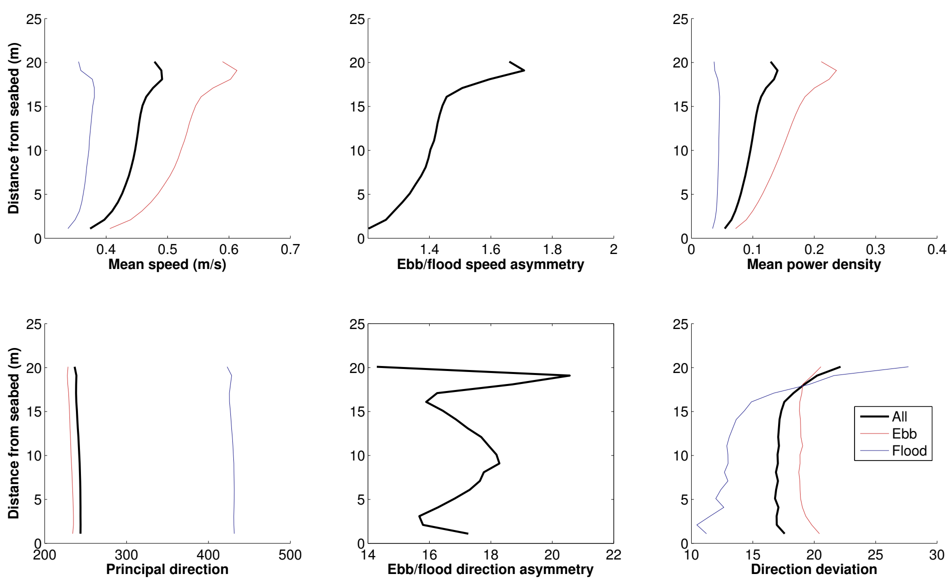

Figure 12: Vertical profile metrics at SS04 in Rich Passage.

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