Reference Model #1 – Tidal Energy: Resource

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1 Introduction

Reference Model #1 is a tidal turbine operating in a narrow, tidal channel. The site is a generalized version of Tacoma Narrows, Puget Sound, Washington. The resource is a mixed, mainly semidiurnal tidal regime with two ebbs and floods each day of unequal strength (i.e., a diurnal inequality in which a strong ebb/flood exchange is followed by a weak exchange). The diurnal inequalities provide extended windows of weak currents for device installation and maintenance activities relative to a purely semidiurnal tidal regime, though at the expense of reduced generation potential for equivalent peak currents.

Doppler profiler data from Puget Sound are used to construct a reference tidal resource (i.e., a generic mixed, mainly semidiurnal tidal regime). After Polagye and Thomson (*submitted*), currents measured by a Doppler profiler ($\boldsymbol{U}_{\boldsymbol{sample}}$) may be conceptually partitioned into deterministic ($\boldsymbol{U}_{\mathbf{det}}$), meteorological ($\boldsymbol{U}_{\mathbf{met}}$), and turbulent ($\boldsymbol{U}_{\mathbf{turb}}$) components, as well as Doppler uncertainty (n_{sample}) (Brumley et al. 1991).

$$U_{\mathbf{sample}} = U_{\text{det}} + U_{\mathbf{met}} + U_{\mathbf{turb}} \pm n_{\mathbf{sample}}. \tag{1.1}$$

each of which are further subdivided. The deterministic currents include harmonic currents, described by harmonic constituents, as well as the aharmonic response to these currents induced by local topography and bathymetry. Aharmonic currents are not described by tidal constituents, but are repeatable, site-specific flow features. Meteorological currents include wave- and wind-induced motion, residual currents associated with estuarine stratification, and storm surges. Turbulent currents include large-scale, horizontal eddies and small-scale, isotropic turbulence.

In order to evaluate device performance, a generalized probability distribution and vertical profile for current speeds in a mixed, mainly semidiurnal tidal regime is required. Once the distribution of velocities is known, leading-order device performance may be evaluated based on the device operating parameters at each point on the distribution. These parameters include cut-in speed, rated speed, and power conversion efficiency.

2 Methodology

Doppler profiler measurements from sites in Puget Sound with utility-scale potential are summarized in Table 1. Details for northern Admiralty Inlet are given in Figure 1 and Tacoma Narrows in Figure 2. While the reference site is patterned after Tacoma Narrows, there are a limited number of measurements for this location. Therefore, it is desirable to expand the basis for the generalized distribution to include other energetic sites in Puget Sound.

Table 1 – ADCP measurement detail for Puget Sound, Washington

Site	Depth (m)	Dates	Duration (days)	Vertical Resolution (m)	Ensemble Interval (s)	Source
Northern Admiralty Inlet						
AI-1	85	08/18/07 - 09/19/07	32	2	900	EHI[1]
AI-2	67	08/18/07 - 09/19/07	32	1	900	EHI
AI-4	56	05/20/09 - 08/03/09	75	1	30	NNMREC[2]
AI-5	65	08/05/09 - 11/10/09	97	1	135	NNMREC
AI-6	66	11/12/09 - 01/29/10	78	1	45	NNMREC
AI-7	56	02/11/10 - 05/04/10	82	1	60	NNMREC
AI-8	58	05/06/10 - 07/09/10	64	1	60	NNMREC
Tacoma Narrows						
TN-1	30	05/30/07 - 07/01/07	32	1	900	EHI
TN-2	55	07/02/07 - 08/02/07	31	1	900	EHI

[1]Evans-Hamilton Inc.

[2]University of Washington, Northwest National Marine Renewable Energy Center

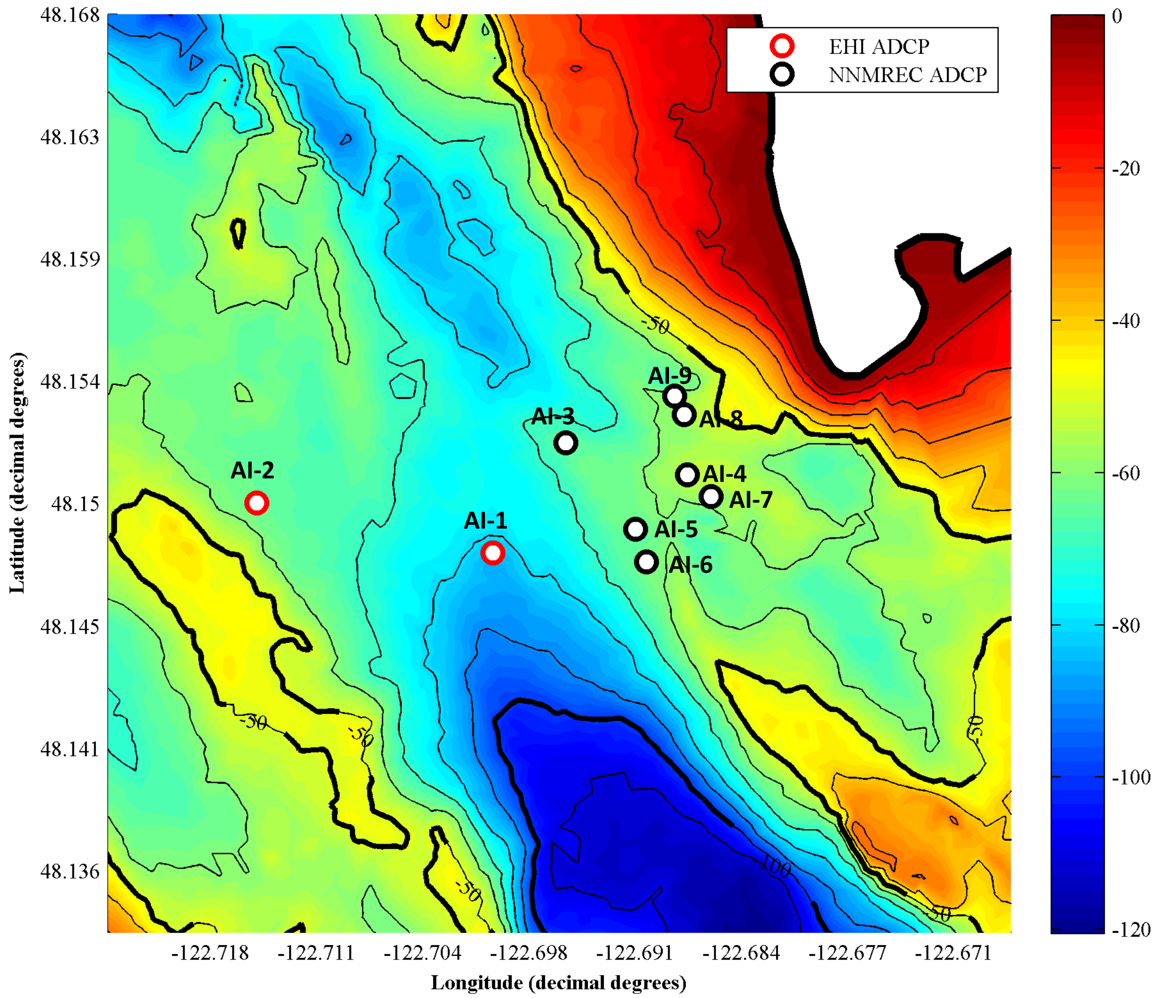

Figure 1 – Admiralty Inlet, Washington ADCP deployment locations superimposed on bathymetry (meters relative to mean lower low water)

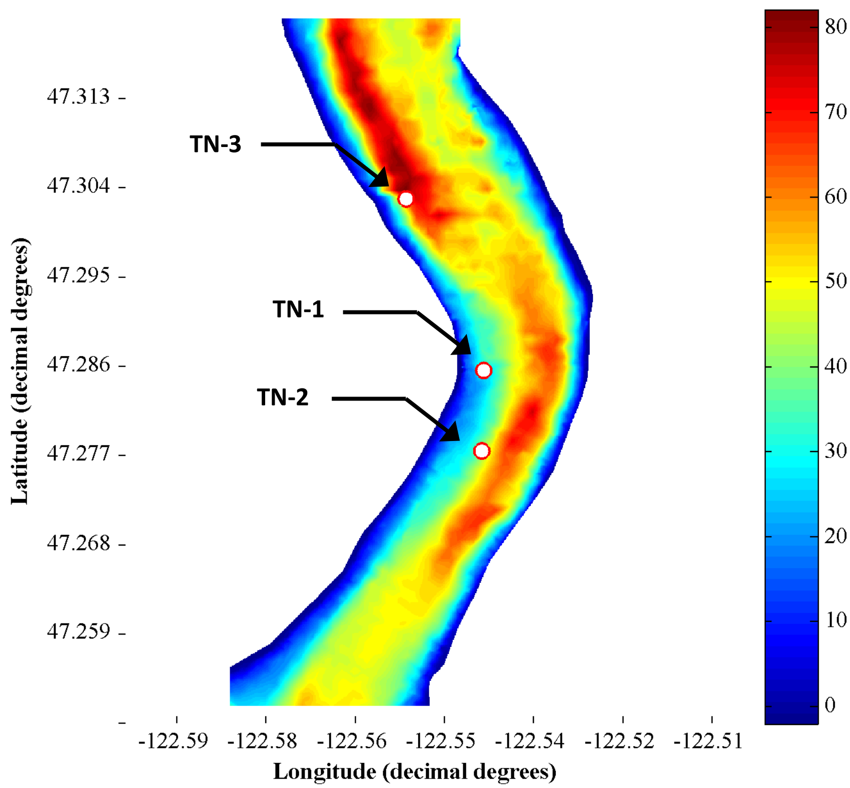

Figure 2 – Tacoma Narrows, Washington ADCP deployment locations superimposed on bathymetry (meters relative to mean lower low water)

In order to directly compare data from the sites listed in Table 1, all measurements are converted to a 15 minute (900 s) ensemble ($\boldsymbol{U}_{\text{ensemble}}$). This greatly reduces the contribution of turbulence (Thomson et al. *in revision*),

$$U_{\text{ensemble}} = \overline{U_{\text{sample}}} = \overline{U_{\text{det}} + U_{\text{met}} + U_{\text{turb}} \pm n_{\text{sample}}} \approx U_{\text{det}} + U_{\text{met}} \pm n_{\text{ensemble}}, \qquad (2.1)$$

where the overbar denotes the temporal mean. This also reduces ensemble Doppler noise (n_{ensemble}) by a factor of $N^{1/2}$ relative the original Doppler noise (n_{sample}), where N is the number of samples in the ensemble. In comparison to the deterministic component (U_{det}), n_{ensemble} is very small and may be neglected. The fifteen minute ensembles are also likely to smooth the aharmonic component. In Polagye and Thomson (*submitted*), a five minute ensemble is recommended in order to preserve the deterministic and meteorological components, while filtering out the turbulent component and Doppler noise. However, this is shorter than the sample interval for some of the available measurements and it is preferred to treat all measurements consistently. In Puget Sound, storm surges and wind-driven currents are not significant and the primary contributor to meteorological currents is estuarine circulation associated with density gradients. In Polagye and Thomson (*submitted*), it is demonstrated that these residual currents are small in comparison to deterministic currents at mid-water depth, but are significant near the surface and seabed.

The following procedure is applied to derive a generalized probability distribution of tidal currents. As mentioned above, data from each of the sites listed in Table 1 is first standardized to a 15 minute ensemble average. A time series of current speed (absolute value of horizontal velocity) is then extracted at mid-water depth, such that the deterministic component of the tidal currents dominates over the meteorological component. The series is then normalized by the maximum ensemble-average speed in the time series (U_{max}),

$$U_{\text{norm}} = \frac{|U_{\text{ensemble}}|}{U_{\max}} \tag{2.2}$$

and distributed into equal-size bins ranging from zero to one. The average of these normalized distributions for all sites is taken as a generalized velocity distribution for a mixed, mainly semi-diurnal tidal regime.

The vertical profile associated with this generalized distribution is selected by inspection of the mean vertical profile for all sites in Table 1. This is given in the form of a power law

$$U(z) = U_{0.5}\left(\frac{2z}{D}\right)^{1/\alpha} \tag{2.3}$$

where $U_{0.5}$ is the mid-water current speed, z is the depth of interest, D is the water depth, and α is the empirical power law exponent. Three aspects of this approach are worth noting. First, it is a considerable oversimplification to assume that the vertical profile is constant over all tidal cycles. Analyses (B. Polagye, unpublished results) show that the power law exponent (α) that best describes the vertical profile varies with the strength and direction of the currents. Second, α is rarely single-valued for a given current velocity (e.g., at U/U_{max} = 0.5, α will take on a range of values depending on whether these currents are observed during an accelerating or decelerating portion of the tidal cycle). Third, while commonly used in wind and hydrokinetic applications, the power law description of the vertical profile lacks physical basis. A log layer description based on bottom roughness and shear velocity may be preferable in future reference models.

3 Results

The distribution of normalized velocities in Puget Sound and the reference distribution are shown in Figure 3 and the values for the reference distribution are given in Table 2.

Table 2 – Reference resource distribution for a mixed, mainly semidiurnal tidal regime

U/U_{max}	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
Frequency	0.041	0.133	0.151	0.157	0.150	0.136	0.103	0.071	0.040	0.016	0.003

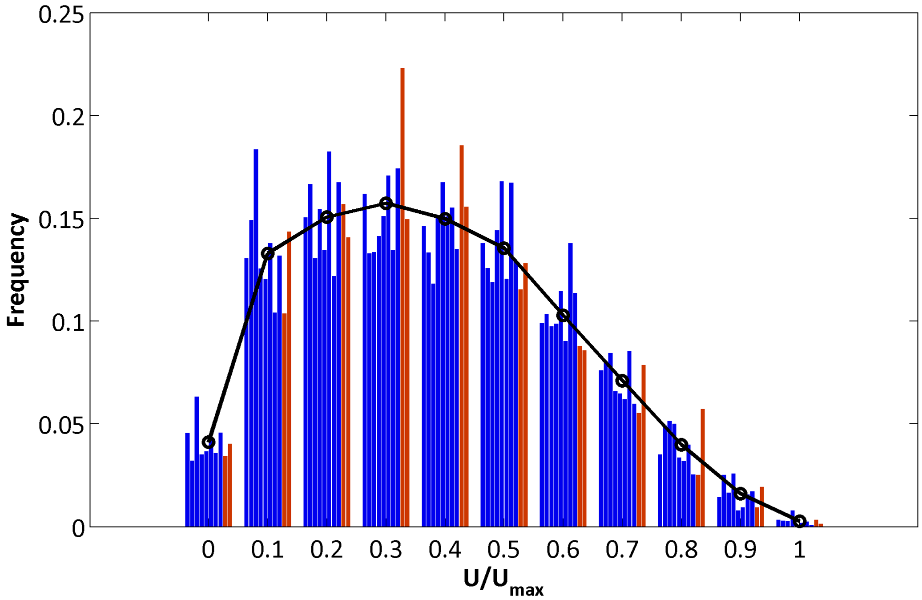

Figure 3 – Normalized velocity distributions for sites in Puget Sound. Blue bars denote sites in northern Admiralty Inlet. Red bars denote sites in Tacoma Narrows. The black line denotes the generalized velocity distribution for the reference model (mean of all sites).

Figure 4 shows vertical profiles for all sites in Puget Sound and the generalized, reference profile. In all cases, the profiles represent the average power law fit for all measurements at a given location. By inspection, the black line, which denotes a $1/7^{th}$ power law profile, is roughly in the middle of the observed profiles. Since this profile has been used in prior studies (e.g., EPRI feasibility assessments), it is selected as the reference profile.

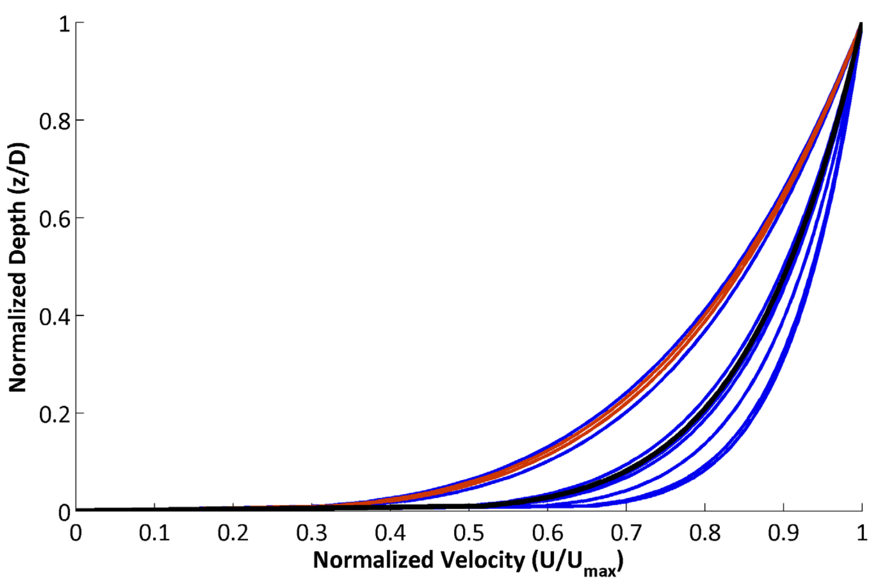

Figure 4 – Normalized velocity profiles for sites in Puget Sound. Blue profiles denote locations in northern Admiralty Inlet. Red bars denote sites in Tacoma Narrows. The black line is a power law profile with a $1/7^{th}$ exponent, chosen by inspection to represent the reference model distribution.

4 Discussion

The reference distribution given in Table 2 may be combined with the 1/7th power law profile and any reasonable value for U_{max} to yield a hub-height velocity distribution for tidal device performance evaluation. Based on data from Puget Sound (Polagye and Thomson *submitted*), 3 m/s is a reasonable value for U_{max}. This representation of the currents for performance evaluation is extremely compact, but also extremely idealized.

First, the turbulent component of the tidal currents is significant (Thomson et al. *in revision*), but excluded from this representation. Note that, in general, the relation between turbulence and device performance has not been established for hydrokinetic turbines. Second, off-axis inflow conditions are likely, due to directional variations within the tidal cycle and asymmetries between the direction of ebb and flood (i.e., ebb and flood not bidirectional). A more complete description of the tidal currents might be given by a joint probability distribution of velocity with direction. Third, as previously discussed, a single-valued power law exponent does not provide a complete or physically-justified description of the vertical structure of the tidal currents. These limitations could be addressed by future reference modeling efforts as their relative importance is clarified through device testing and modeling.

5 Conclusions

Doppler profiler data from Puget Sound serves as a basis for a reference distribution and vertical profile of current velocities for a mixed, mainly semidiurnal tidal regime. This representation is suitable for estimating leading-order device performance in the reference resource. The limitations of this representation are briefly discussed.

6 References

Brumley, B.H., Cabrera, R.G., Deines, K.L, and Terray, E.A. Performance of a Broad-Band Acoustic Doppler Current Profiler, *IEEE Journal of Oceanic Engineering*, 1991, 16(4), 402-407.

Polagye, B. and J. Thomson (*submitted*), Tidal energy resource characterization: methodology and field study in Admiralty Inlet, Puget Sound, US.

Thomson, J., B. Polagye, V. Durgesh, and M. Richmond (*in revision*) Measurements of turbulence at two tidal energy sites in Puget Sound, WA (USA).