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The Influence of a Slack Current Threshold on Tidal Energy Resource Characterization

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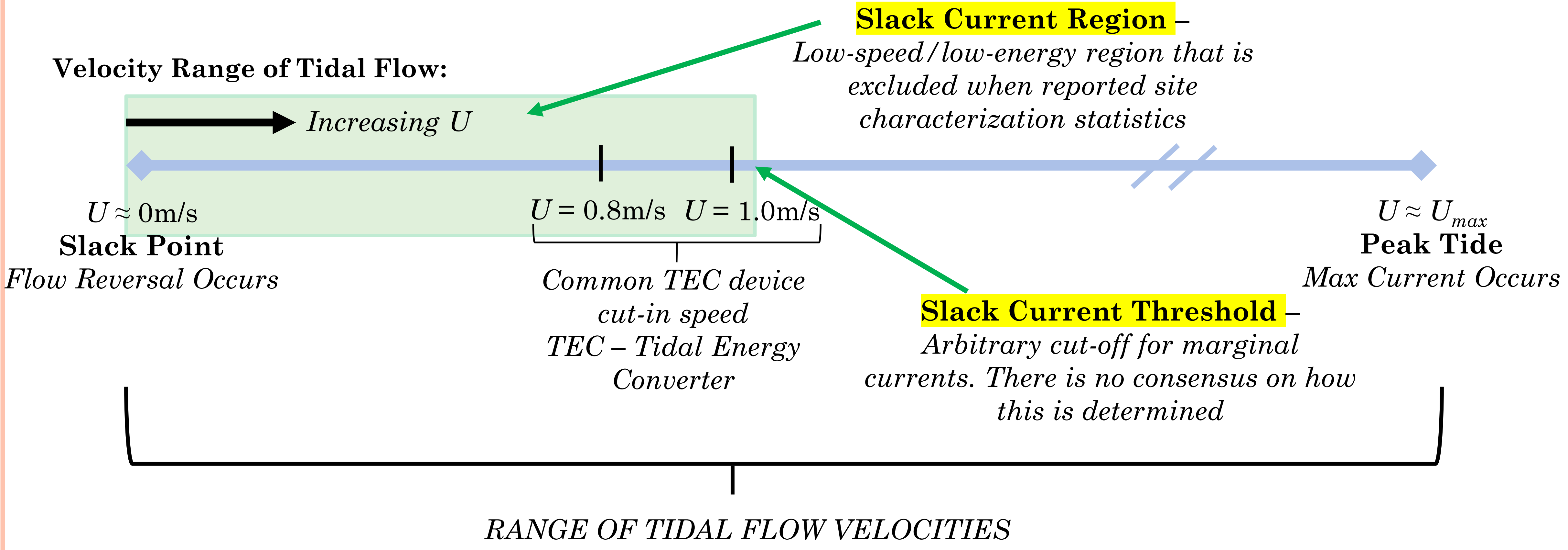
Slack Current / Slack Current Threshold

What is meant by slack current threshold?

Velocity Range of Tidal Flow:



***Note*:** In oceanography, “slack current” often refers to when the water is completely unstressed, where U=0m/s. This is NOT the definition used in this study.

Introduction

Slack Current Definitions in Literature

- the period at the turn of the tide when there is little or no horizontal motion of tidal water

  Merriam-Webster Dictionary

- the weakest currents that occur between the flood and ebb currents

  National Oceanic and Atmospheric Administration

- the period of time during which the marine and hydrokinetic (MHK) devices are unable to extract energy from the flow

  National Laboratory

- periods of little or no flow between tides

  Private Company in Tidal Energy Industry

- range for which flow turbulence nature is of minor importance for tidal current energy exploitation so that it can be neglected

  University Researcher

Why are slack tides important in the tidal energy community?

★ 1. SITE CHARACTERIZATION ★ (the focus of the current study)

- Slack currents and the selected ***slack current threshold*** affects critical inflow characterization metrics (i.e. mean velocities, turbulence intensity values, and power spectra)
  - These metrics influence:
    - TEC device size
    - TEC material selection
    - Device lifespan estimates
    - Component lifespan estimates
    - Energy production estimates

*The effect of **slack current threshold**:*
At the Nodule Point tidal energy test site, we see a 44% difference in mean velocity and a 93% difference in turbulence intensity depending on the slack current threshold selected.

2. OPERATIONS: Deployment – Maintenance -- Retrieval

MOTIVATION

Open Questions:
- Are any characterization metrics (mean velocity, turbulence intensity, available power, power spectra etc.) sensitive to the Slack Current Threshold? If so, how sensitive?
- How can we establish an industry standard for the Slack Current Threshold?

Note: Formulaically, available power estimates are also highly sensitive to inflow speeds (cubed relationship) and can significantly affect preliminary estimates at tidal sites.

$$I_U = \frac{\sqrt{\overline{u'u'}}}{U} \times 100$$

u' – instantenous vel. fluctuation
U – average inflow velocity

$$P = \frac{1}{2}\rho A U^3$$

ρ – water density
A – rotor swept area
U – average inflow velocity

- Selecting the Slack Current Threshold **should not** be arbitrary.
  - Many papers site device cut-in speed as the justification for a chosen slack current threshold.
  - Preliminary site characterization and device power estimates should be device agnostic

In Literature and Industry

Slack Current Threshold in Literature

Site	Location	Author	Slack Current Threshold
Goto Islands	Japan	Nova and Kyozuka (2019)	$U \leq 0.70$m/s
Nodule Point	Washington, USA	Thomson et al. (2012)	$U \leq 0.80$m/s
Admiralty Inlet	Washington, USA	Thomson et al. (2012)	$U \leq 0.80$m/s
East River	New York, USA	Gunawan et al. (2014)	$U \leq 1.00$m/s
Sound of Islay	Scotland, UK	Milne (2013)	$U \leq 1.00$m/s
Strangford Lough	Northern Ireland, UK	MacEnri et al. (2013)	$U \leq 1.00$m/s

Tidal Energy Device Cut-in Speed

Device Name	Developer	Cut-in Speed
Nova M100	Nova Innovation Ltd	0.50m/s
SeaGen – 1.2MW	Marine Current Turbines	0.70m/s
Evopod	Ocean Flow Energy	0.70m/s
SCHOTTEL 54 kW	SCHOTTEL	0.70m/s
SCHOTTEL 70 kW	SCHOTTEL	0.90m/s
HS1000	Andritz Hydro Hammerfest	1.00m/s
AR-1500	Atlantis Resources Corp.	1.00m/s
AR-2000	Atlantis Resources Corp.	1.00m/s
ATIR	Magallanes Renovables	1.00m/s
SeaGen S – 2MW	Marine Current Turbines	1.00m/s
1MW Alstom Tidal Turbine	Alstom	1.00m/s
Gen 5 Free Flow System	Verdant Power	1.00m/s
SR 2000 Tidal Turbine	Scotrenewables	1.00m/s

Relevant Specifications and Standards

- Marine Energy Classification White Paper **IEC TC 114 USTAG November 2021** (Vincent S. Neary, Kevin A. Haas, and Jonathan A. Colby)
    - Title: Marine Energy Classification Systems: Tools for resource assessment and design
    - Design goals and requirements:
        - Classification should be technology agnostic
        - Classification should conform to international, consensus-based standards, such as those developed by the IEC under Technical Committee 114: Marine energy – Wave, tidal and other water current converters
        - Classification systems should be based on three parameters or less but designed to be flexible to adapt to new knowledge and experience

WIND TURBINE CLASSIFICATION [IEC 61400-1]

Power Class		I	II	III	S
U_{ref} (m/s)		50	42.5	37.5	Value specified by engineer
U_{avg} (m/s)		10	8.5	7.5	
A	I_{ref}(-) @15 m/s	0.16			
B		0.14			
C		0.12			

Exhibit 1. Existing Wind Turbine Classification system based on a reference windspeed, average windspeed, and turbulence intensity at a reference windspeed of 15m/s

TIDAL DEVICE CLASSIFICATION

Class		I	II	III	S
U_{ref} (m/s)		3.5	2.5	2.0	Specified by engineer
A	I_{ref}(-) @1.5 m/s	0.20			
B		0.15			
C		0.10			

Exhibit 2. Proposed Tidal Device Classification system based on a reference flow speed and turbulence intensity at a reference flow speed of 1.5m/s

TIDAL CONDITIONS AT US PROJECT SITES

Project	Reference	Site measurement		Design condition		TEC Class
		U_{ref} (m/s)	I_{ref}	U_{ref} (m/s)	I_{ref}	
RITE	Gunawan et 1. 2014	2.4	0.18	2.5	0.20	IIA
Admiralty Inlet	Thomson et al. 2012	2.0	0.09	2.5	0.10	IIIC
Nodule Point	Thomson et al. 2012	2.6	0.10	3.5	0.10	IC

Exhibit 3. Example of classification results using the system proposed in Exhibit 2.

- **IEC TS 62600-2 ED2 AND IEC TS 62600-201 ED2**
    - Title: Marine energy – Wave, tidal and other water current converters
      Part 2: Design requirements for marine energy systems.
      Part 201: Tidal energy resource assessment and characterization
        - Goal is to "… provide a uniform methodology that will ensure consistency and accuracy in the estimation, measurement, characterization and analysis…"
        - However, this standard **DOES NOT list slack condition instructions** in "Results presentation" guidance.

CURRENT STUDY

GOAL: Perform tidal energy site characterizations studying the effect of a slack current threshold of: **0.6m/s**, **0.8m/s**, and **1.0m/s**

Acoustic Doppler Velocimeter (ADV) data was collected from the following sites in an effort to perform a tidal energy resource characterization:

East River, New York City, USA
Verdant Power, Inc

Nodule Point, Puget Sound, WA, USA
University of Washington

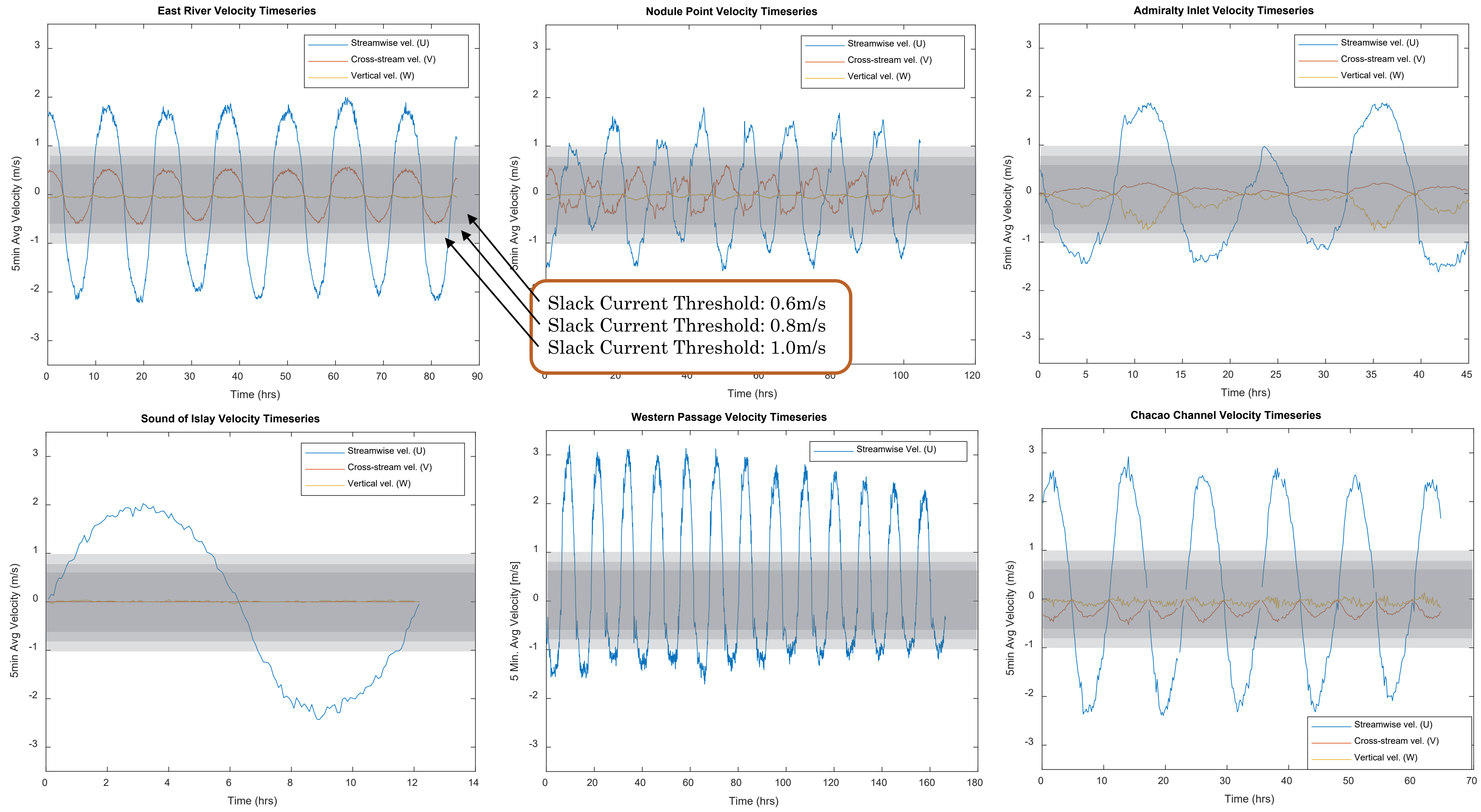
Admiralty Inlet, Puget Sound, WA, USA
University of Washington

Sound of Islay, Scotland, UK
The University of Auckland

Western Passage, Maine, USA
National Renewable Energy Laboratory

Chacao Channel, Chile
University of Washington

Current Slack Threshold and Velocity Time Series



Slack Current Threshold and Flow Characterization

EAST RIVER

Percent of collected data considered to be in slack conditions

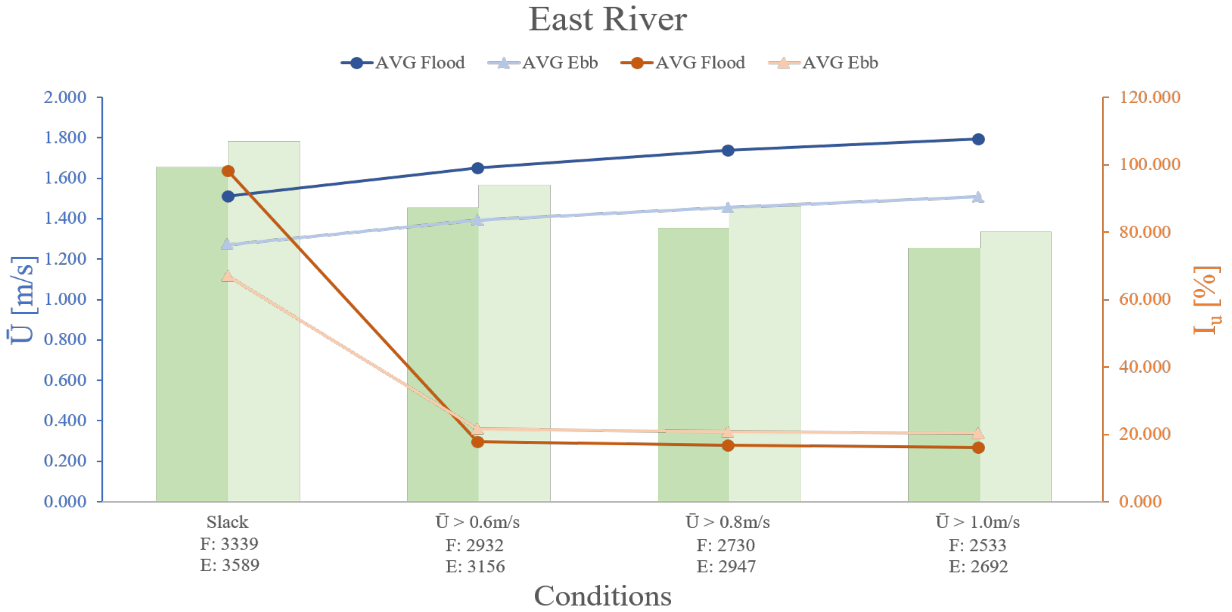
Site		$\bar{U}$ < 0.6m/s	$\bar{U}$ < 0.8m/s	$\bar{U}$ < 1.0m/s
East River	Flood	12.2%	18.2%	24.1%
	Ebb	12.1%	17.9%	25.0%

Effect of Slack Current Threshold on: *AVG $\bar{U}$*

		$\bar{U}$ > 0.6m/s	$\bar{U}$ > 0.8m/s	$\bar{U}$ > 1.0m/s
AVG $\bar{U}$	Flood	1.65	1.74	1.80
	Ebb	1.39	1.46	1.51
% Diff from $\bar{U}$ > 0.6m/s	Flood	-	5.45%	9.09%
	Ebb	-	5.04%	8.63%

Effect of Slack Current Threshold on: *AVG I_u*

		$\bar{U}$ > 0.6m/s	$\bar{U}$ > 0.8m/s	$\bar{U}$ > 1.0m/s
AVG I_u	Flood	17.78	16.85	16.12
	Ebb	21.68	20.83	20.27
% Diff from $\bar{U}$ > 0.6m/s	Flood	-	5.23%	9.34%
	Ebb	-	3.92%	6.50%



Power Available Estimates

(Assuming Gen 5 Free Flow System Turbine)

	$\bar{U}$ < 0.6m/s	$\bar{U}$ < 0.8m/s	$\bar{U}$ < 1.0m/s
Flood	45.19kW	53.00kW	58.67kW
Ebb	27.02kW	31.31kW	34.64kW

TAKEAWAY: Velocity input has a **cubed** effect on power estimation, causing a **30% difference** in results

Slack Current Threshold and Flow Characterization

All Sites

Percent of collected data considered to be in slack conditions

Site		$\bar{U} < 0.6$m/s	$\bar{U} < 0.8$m/s	$\bar{U} < 1.0$m/s
East River	Flood	12.2%	18.2%	24.1%
	Ebb	12.1%	17.9%	25.0%
Nodule Point	Flood	31.6%	43.4%	57.2%
	Ebb	32.3%	46.3%	66.1%
Admiralty Inlet	Flood	29.4%	36.4%	45.6%
	Ebb	18.3%	30.8%	43.3%
Sound of Islay	Flood	17.3%	22.7%	29.3%
	Ebb	15.5%	16.9%	21.1%
Western Passage	Flood	6.9%	10.5%	14.2%
	Ebb	23.4%	38.1%	56.9%
Chacao Channel	Flood	11.1%	16.8%	21.2%
	Ebb	16.1%	21.1%	26.7%

Conclusions

- Sites with lower flow speeds can have over 50% of the flow considered slack depending on the slack current threshold
- Variability is not only found from site-to-site, but also between flood and ebb tides at each site.

Possible Implications

- Inaccurate estimation of project viability

Slack Current Threshold and Flow Characterization

All Sites

AVG Mean Velocity, $\bar{U}$

Site		AVG $\bar{U}$ *[m/s]*			% Diff from $\bar{U}$ > 0.6m/s	
		$\bar{U}$ > 0.6m/s	$\bar{U}$ > 0.8m/s	$\bar{U}$ > 1.0m/s	$\bar{U}$ > 0.8m/s	$\bar{U}$ > 1.0m/s
East River	Flood	1.65	1.74	1.80	5.45%	9.09%
	Ebb	1.39	1.46	1.51	5.04%	8.63%
Nodule Point	Flood	1.10	1.19	1.28	8.18%	16.36%
	Ebb	1.03	1.11	1.24	7.77%	20.39%
Admiralty Inlet	Flood	1.40	1.47	1.57	5.00%	12.14%
	Ebb	1.13	1.20	1.27	6.19%	12.39%
Sound of Islay	Flood	1.51	1.56	1.63	3.31%	7.95%
	Ebb	1.75	1.76	1.81	0.57%	3.43%
Chacao Channel	Flood	1.89	1.97	2.03	4.23%	7.41%
	Ebb	1.64	1.70	1.76	3.66%	7.32%

Conclusions

- Some sites exhibit >10% difference in mean velocity based on the slack current threshold

Possible Implications

- Over/Under estimation of power available at the site
- Faulty estimations of loadings, fatigue, and device lifespan

Slack Current Threshold and Flow Characterization

All Sites

AVG Turbulence Intensity, I_u

Site		AVG I_u [%]			% Diff from $\bar{U}$ > 0.6m/s	
		$\bar{U}$ > 0.6m/s	$\bar{U}$ > 0.8m/s	$\bar{U}$ > 1.0m/s	$\bar{U}$ > 0.8m/s	$\bar{U}$ > 1.0m/s
East River	Flood	17.78	16.85	16.12	5.23%	9.34%
	Ebb	21.68	20.83	20.27	3.92%	6.50%
Nodule Point	Flood	9.32	9.15	9.13	1.82%	2.04%
	Ebb	9.70	9.74	9.67	0.41%	0.31%
Admiralty Inlet	Flood	8.08	7.46	6.95	7.67%	13.99%
	Ebb	7.54	7.03	6.65	6.76%	11.80%
Sound of Islay	Flood	13.75	13.75	13.91	0.00%	1.16%
	Ebb	11.34	11.36	11.41	0.18%	0.62%
Chacao Channel	Flood	13.40	13.32	13.32	0.60%	0.60%
	Ebb	13.51	13.36	13.36	1.11%	1.11%

Conclusions

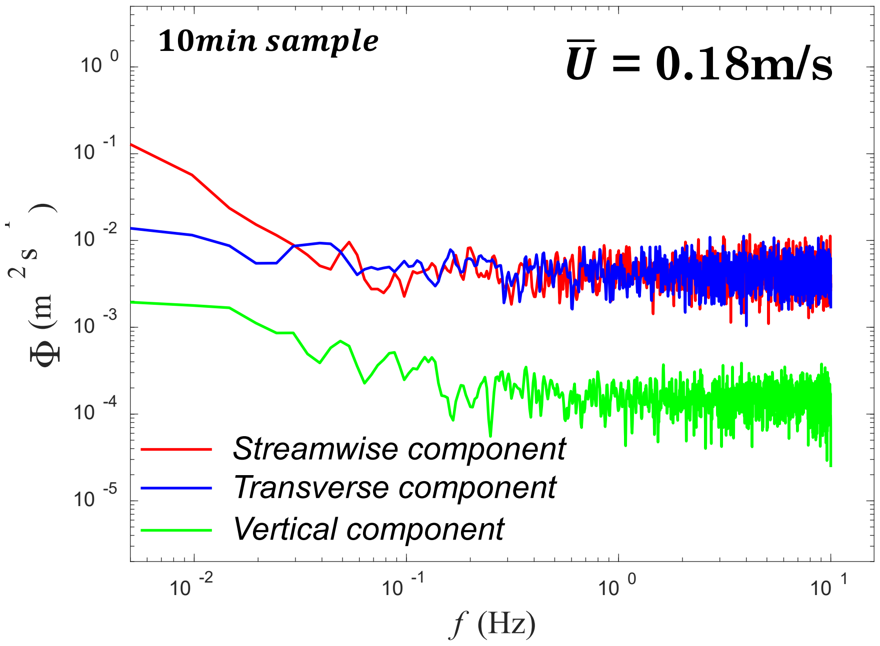
- Some sites exhibit >10% difference in turbulence intensity based on the slack current threshold
- For other sites, turbulence intensities are marginally affected by the choice of the slack current threshold

Possible Implications

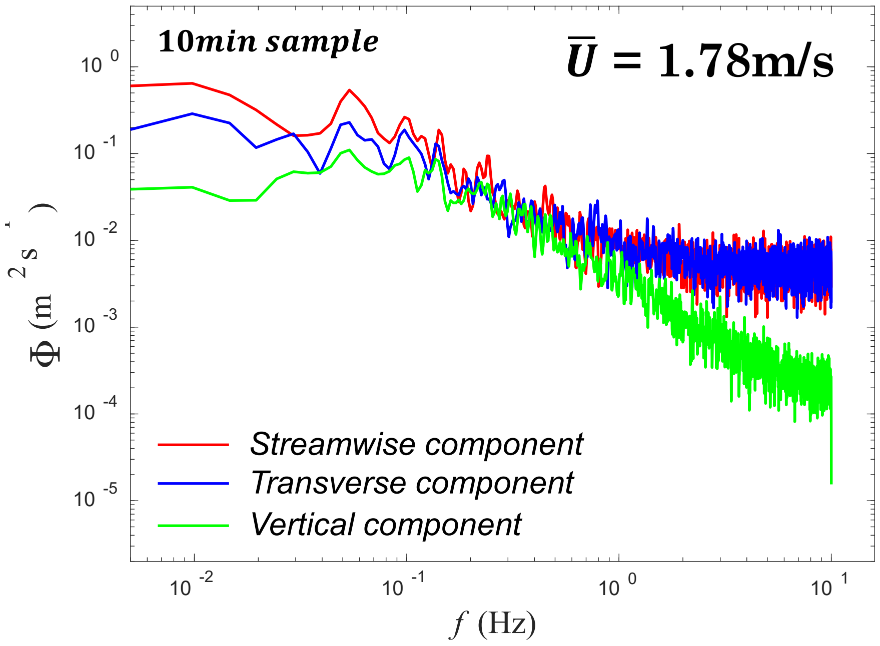
- Faulty estimations of loadings, fatigue, and device lifespan

SPECTRA IN SLACK VS. PEAK FLOW CONDITIONS

East River *U-V-W* Spectra during slack tide



East River *U-V-W* Spectra during non-slack tide

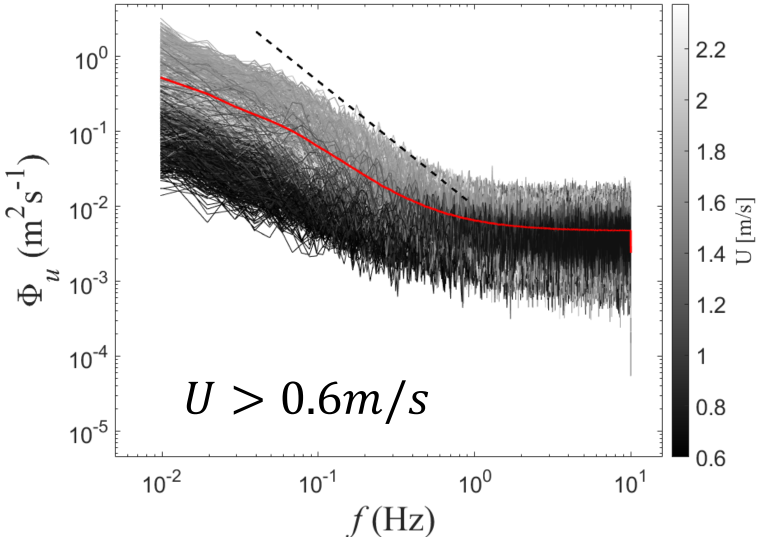


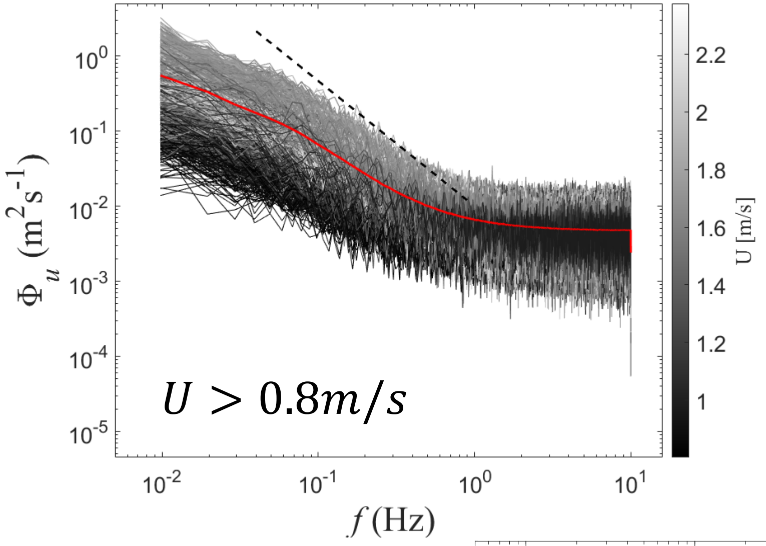
The resulting power spectra densities in slack tides show lesser energy in the flow at all scales compared to peak flow conditions. Additionally, no inertial subrange is seen in slack tides.

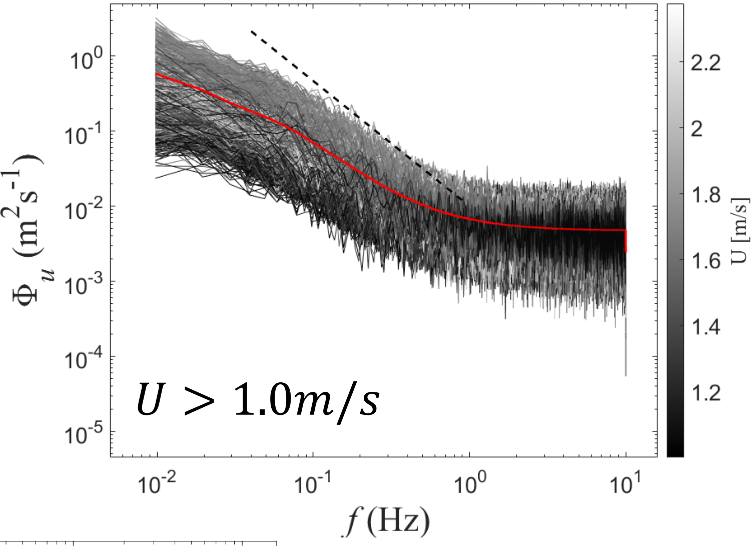
Effect of Slack Current Threshold on Spectra

East River

Red line indicates ensemble average of spectra

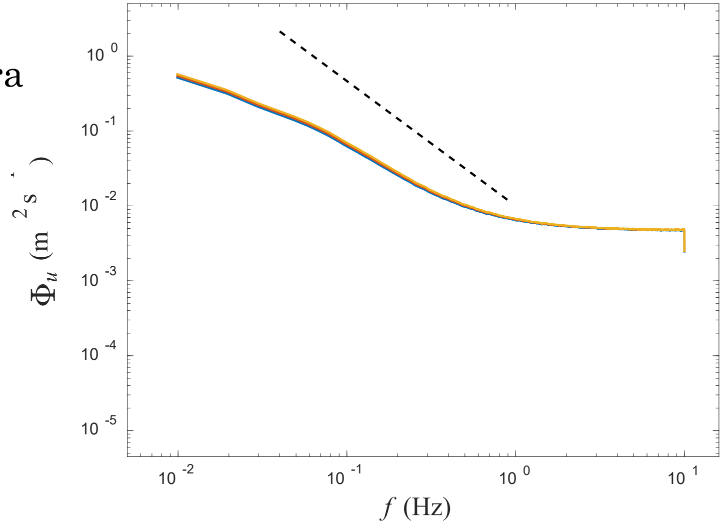






Comparing ensemble-averaged spectra

U > 0.6m/s
U > 0.8m/s
U > 1.0m/s



No effect on ensembled-averaged spectra

Conclusions

- The entire tidal energy community benefits from consistent standards and guidance in resource characterization to allow apple-to-apple comparisons between sites.
- There currently is no such universal and consistent standards/guidance regarding the consideration of slack tides when characterizing a tidal energy site making it difficult to compare inflow data between different sites.
- Resource characterization should be device agnostic, at least for preliminary estimations, making cut-in speeds an undesirable metric to base slack current threshold.
- The selection of a slack current threshold may have a substantial influence on statistics such as site-averaged velocities, turbulence intensities, and available power estimates.
    - At Admiralty Inlet, when the slack current threshold is changed from 0.6m/s to 1.0m/s, we see a 12.4% increase in mean velocity and 14% reduction in turbulence intensity.
    - The slack current threshold does not impact ensemble-average spectra at a tidal energy site
- More focus is needed to establish industry-approved standards in reporting statistics for a tidal resource assessment.

APPENDIX

Slack Current Threshold and Turbulence Statistics

- Blue axis indicates 5min streamwise mean velocity averages
- Orange axis indicates 5min streamwise mean turbulence intensity values
- Green bars indicate the number of 5min flood (darker green) and ebb (lighter green) samples incorporated at each slack threshold value. Note, the bars are included to show the trend of how much data is omitted per raise in threshold; exact magnitude is not critical. However, for convenience, numerical exact magnitudes are included for flood (F) and ebb (E) under each plot.

Effect of Slack Current Threshold on: *AVG $\bar{U}$*

		$\bar{U}$ > 0.6m/s	$\bar{U}$ > 0.8m/s	$\bar{U}$ > 1.0m/s
AVG $\bar{U}$	Flood	1.65	1.74	1.80
	Ebb	1.39	1.46	1.51
% Diff from $\bar{U}$ > 0.6m/s	Flood	-	5.45%	9.09%
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Effect of Slack Current Threshold on: *AVG I_u*

		$\bar{U}$ > 0.6m/s	$\bar{U}$ > 0.8m/s	$\bar{U}$ > 1.0m/s
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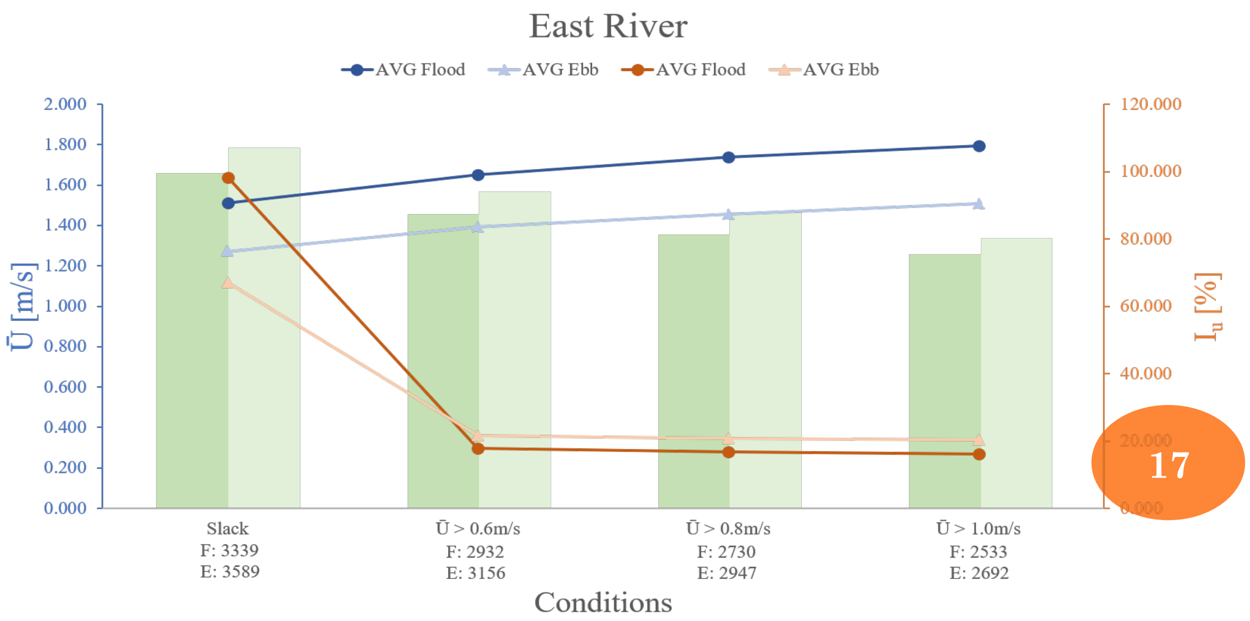
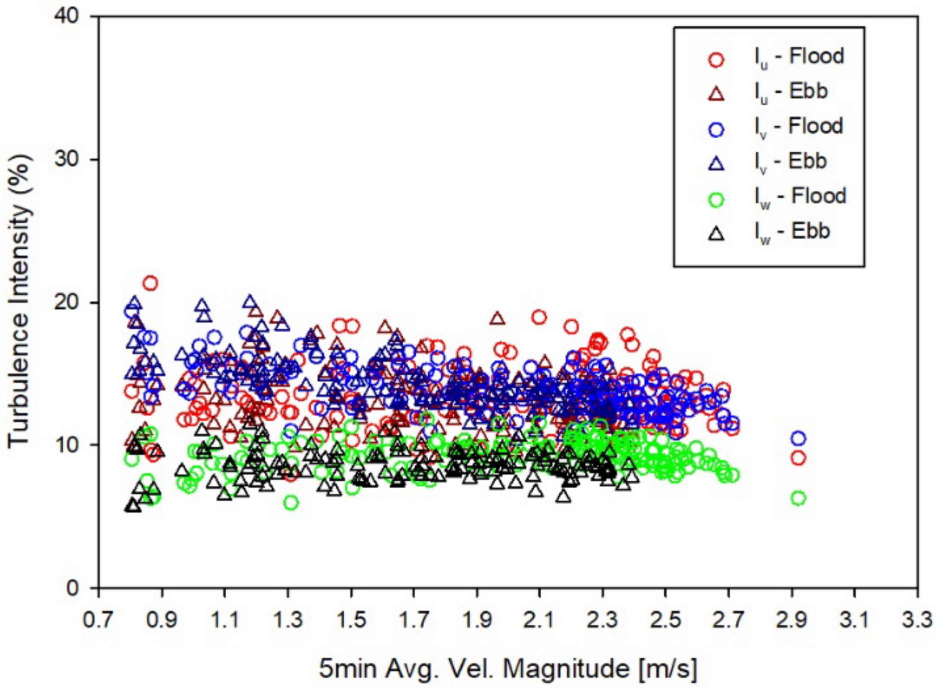


Slack vs No Slack - Comparison

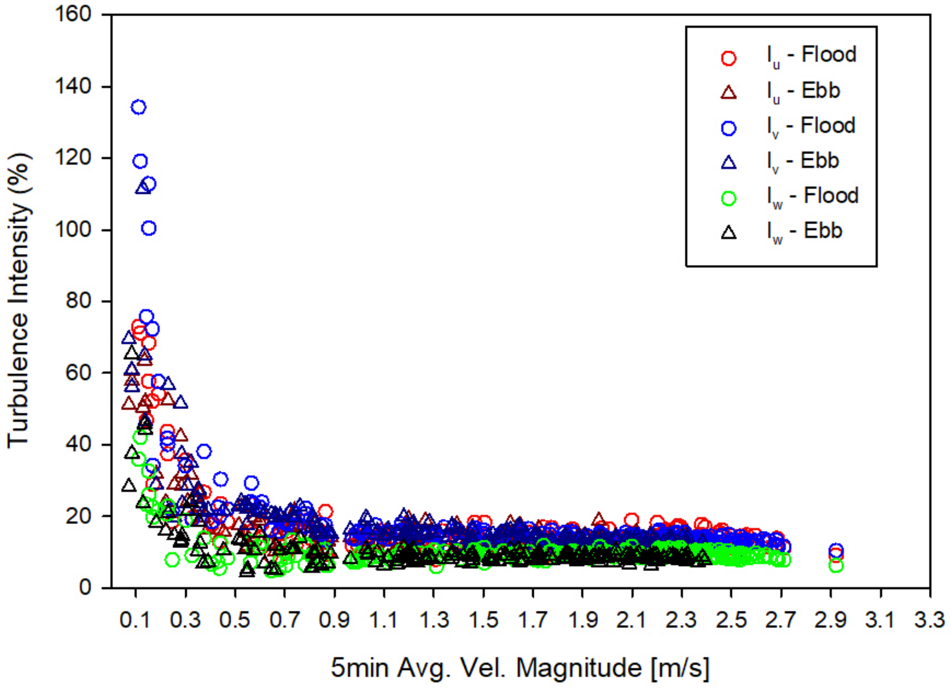
$$I_u = \frac{\sigma(u)}{U},\ I_v = \frac{\sigma(v)}{U},\ I_w = \frac{\sigma(w)}{U}$$

Chacao Channel

$$z^* = 0.263$$



EXCLUDING
slack conditions



INCLUDING
slack conditions