



Characterizing the Marine Energy Test Area (META) in Wales, UK

Neill, Simon; Fairley, Ian; Rowlands, Steven; Young, Saul; Hill, Tom; Unsworth, Christopher; King, Nicholas; Roberts, Michael; Austin, Martin; Hughes, Peter; Masters, Ian; Owen, Aled; Powell, Ben; Reeve, Dominic E.; Lewis, Matthew

Renewable Energy

DOI:

[10.1016/j.renene.2023.01.105](https://doi.org/10.1016/j.renene.2023.01.105)

E-pub ahead of print: 01/03/2023

Peer reviewed version

[Cyswllt i'r cyhoeddiad / Link to publication](#)

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):

Neill, S., Fairley, I., Rowlands, S., Young, S., Hill, T., Unsworth, C., King, N., Roberts, M., Austin, M., Hughes, P., Masters, I., Owen, A., Powell, B., Reeve, D. E., & Lewis, M. (2023). Characterizing the Marine Energy Test Area (META) in Wales, UK. *Renewable Energy*, 205, 447-460. <https://doi.org/10.1016/j.renene.2023.01.105>

Hawliau Cyffredinol / General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1 Characterizing the Marine Energy Test Area (META)
2 in Wales, UK

3 Simon P. Neill^{a,*}, Iain A. Fairley^b, Steven Rowlands^a, Saul Young^c, Tom
4 Hill^c, Christopher A. Unsworth^a, Nicholas King^b, Michael J. Roberts^a,
5 Martin J. Austin^a, Peter Hughes^a, Ian Masters^b, Aled Owen^a, Ben Powell^a,
6 Dominic Reeve^b, Matthew J. Lewis^a

^a*School of Ocean Sciences, Bangor University, Menai Bridge, LL59 5AB, UK*

^b*Faculty of Science and Engineering, Swansea University, Swansea, SA1 8EN, UK*

^c*Marine Energy Wales, Pier House, Pembroke Dock, SA72 6TR, UK*

7 **Abstract**

8 With lack of convergence on any single wave or tidal technology, test centres
9 have a unique role in the marine renewable energy industry. Test centres
10 facilitate real testing at sea for devices and components at various TRLs
11 (Technology Readiness Level), reducing the time, cost, and risks faced by
12 marine energy developers. META (Marine Energy Test Area) is a £2.7M
13 project managed by Marine Energy Wales (MEW), consisting of eight test ar-
14 eas in the Milford Haven Waterway and surrounding waters (Pembrokeshire,
15 Wales). Although various datasets have been collected from the META test
16 areas over the last decade, and some aspects of these data have been pub-
17 lished in various reports, the data has not been gathered together, system-
18 atically analyzed and critically assessed – the aim of this study. Here, we
19 describe and interpret the various META datasets, including multibeam,
20 ADCP (acoustic Doppler current profiler), and wave buoy data. We report
21 the key parameters of relevance to testing at META, including bathymetry,
22 the nature and magnitude of the tidal currents, turbulence, and wave cli-
23 mates. We make recommendations on future priorities for data collection
24 at META, and discuss the future of the test areas, including expansion into
25 floating wind and other evolving marine energy technologies.

26 *Keywords:* Tidal energy, Wave energy, Acoustic Doppler Current Profiler,
27 Wave buoy, Multibeam echosounder, Turbulence

*Corresponding author

Email address: s.p.neill@bangor.ac.uk (Simon P. Neill)
Preprint submitted to Renewable Energy

January 17, 2023

28 1. Introduction

29 Since EMEC (European Marine Energy Centre) was established in 2003,
30 ocean renewable energy test centres have assumed an important role in the
31 evolution of the industry [1]. Ocean energy test centres provide facilities
32 where either smaller scaled devices, or devices that are at early stages of
33 development, can be tested in relatively sheltered real sea conditions, repre-
34 senting the next steps in technology progression following tank testing [2].
35 They can also offer facilities where larger prototypes can be tested in more en-
36 ergetic conditions, but in pre-consented, and often grid-connected, locations
37 [3]. So far, 12 wave and 15 tidal energy developers have tested their tech-
38 nologies at EMEC, and other test centres have emerged around the world,
39 including FORCE (Fundy Ocean Research Centre for Energy) in Canada,
40 and PMEC (Pacific Marine Energy Centre) in the USA [1]. Although a
41 number of commercial projects are under development in the UK, and test
42 facilities beyond EMEC have been created (e.g. WaveHub and FabTest), the
43 formation of META (Marine Energy Test Area) in Pembrokeshire (Wales)
44 complements these existing facilities.

45 META is a £2.7M project managed by Marine Energy Wales (MEW).
46 META consists of eight pre-consented test areas in the Milford Haven Wa-
47 terway and surrounding waters (Fig. 1), providing the opportunity to test
48 devices, sub-assemblies and components. The mission of META is to reduce
49 the time, cost and risks faced by marine energy developers in order to ac-
50 celerate growth in the sector, whilst complementing the existing test centre
51 network across the UK. Due to the diversity of the marine renewable energy
52 resource and energy markets (e.g. high demand, grid-connected nations, or
53 remote “off-grid” industries), there is no convergent marine energy technol-
54 ogy design [4]. Therefore, META will greatly enhance the range of marine
55 renewable energy technologies that can be tested.

56 META is easily accessible and therefore ideal for early stage developers,
57 and is also a suitable base for research and innovation. Targeting Technology
58 Readiness Level (TRL) 4 – 6, the META sites are non-grid connected, rang-
59 ing from sheltered port-based to open sea, yet accessible, locations. META is
60 part funded by the European Regional Development Fund (ERDF, adminis-
61 tered through the Welsh Government), the Coastal Communities Fund, and
62 the Swansea Bay City Deal¹, and contributes towards plans for Wales to play

¹An investment of up to £1.3 billion in a portfolio of major programmes and projects

63 a key role in a growing global marine renewable energy market. META is
64 well positioned to act as a stepping stone towards full scale deployment at
65 the two offshore demonstration zones in Wales: the North Wales tidal stream
66 demonstration zone [5] and the Pembrokeshire Demonstration Zone (PDZ)
67 [6] for wave and floating wind (South Wales).

68 Over the last decade, various university-led projects have collected data
69 across META to understand and characterize the sites. It is timely to now
70 assess and publish these datasets, including critical analysis and interpre-
71 tation, to characterize the sites in more detail, and to inform future data
72 collection and testing at META.

73 **2. Background to META**

74 META was conceived by Marine Energy Wales to bridge the gap be-
75 tween tank testing and full scale demonstration. META secured funding
76 in 2017 from the European Regional Development Fund, ERDF (adminis-
77 tered through the Welsh European Funding Office, WEFO). This funding
78 initiated the complex licensing and leasing process required to consent the
79 broad design envelope required to install and test a range of novel marine
80 energy technologies, including wave and tidal energy converters. During this
81 process, technology developers participated in surveys to understand their
82 testing requirements, and test sites were identified to meet their current and
83 future needs. The sites were categorized into *Quayside* and *Open Water*
84 (Table 1), with the two categories requiring different levels of consents.

85 The Quayside sites followed a simpler licensing process and were awarded
86 the relevant consents to become operational in September 2019, leading to
87 the first technology trials in 2021 of a novel tidal stream measurement device.
88 The Open Water sites required an Environmental Impact Assessment to be
89 submitted to the marine licensing regulatory body (Natural Resources Wales,
90 NRW). The marine licence for these sites was awarded in January 2021,
91 followed by the Crown Estate Lease in August 2021, making the test centre
92 fully operational, with the first experimental device deployed in November
93 2021. Most of the sites are within the jurisdiction of the Port of Milford
94 Haven, which contains a LNG terminal and hosts a significant number of
95 recreational users. Navigational risk assessment is carried out in dialogue

across the Swansea Bay City Region.

106 with the port. The first deployment at the Open Water sites was a larger
107 scale version of the novel tidal stream measurement device at Warrior Way.
108 The second was a multi-use test buoy used to test floating solar, marine
109 coatings, and a new mooring damper system. Meanwhile, the first full scale
110 generating device will be Bombora Wavepower’s mWave at East Pickard Bay,
111 planned for deployment in Autumn 2022. A further £783,000 of funding was
112 secured for the project from the Swansea Bay City Deal in 2020, ensuring the
113 continual operation and development of the test centre until at least 2025.

104 **3. META data collection**

105 For wave and tidal stream projects, the key dynamical properties to be
106 gathered are those that relate to the power matrices [7] or power curves [8]
107 of wave and tidal energy converters, respectively. Interpolation of the power
108 matrix/curve allows the instantaneous power output for specific devices to be
109 calculated (the technical resource), and so variables such as annual energy
110 yield and capacity factor can be determined [8]. These key variables are
111 significant wave height, wave period (generally the energy wave period), and
112 depth-averaged and depth-varying current speeds. It is also common, while
113 collecting current data, to simultaneously collect data on turbulence, as this
114 affects device performance and loading [9, 10]. In addition, accurate sea bed
115 surveys, particularly those obtained using multibeam echosounders, allow
116 water depths to be determined at each possible device location, highlighting
117 sea bed features that might affect device deployment. Multibeam surveys
118 are usually accompanied by a study of temporal variations in water level so
119 that the water depths under spring and neap conditions can be calculated –
120 this is particularly relevant for devices that would be fixed to the sea bed,
121 since there could be large variations in water depth compared to the mean
122 sea level.

123 *3.1. Multibeam echosounder surveys*

124 SEACAMS I, II (Sustainable Expansion of the Applied Coastal and Ma-
125 rine Sectors) was a £50M European Regional Development Fund (ERDF)
126 programme delivered jointly by Bangor University and Swansea University
127 between 2010 and 2022. The main aim of SEACAMS was to support the
128 development and growth of businesses associated with the marine renew-

129 able energy sector in Wales through the delivery of collaborative RD&I²
130 projects. As part of several such projects and the META initiative, numer-
131 ous multibeam echosounder (MBES) surveys of the Milford Haven Waterway
132 and surrounding areas were conducted in 2013 and 2017. Data was acquired
133 using a frame-mounted SeaBat 7101 multibeam system deployed through a
134 ‘moon-pool’ situated on the rear deck of a 7.9 m Cheetah catamaran survey
135 vessel. The MBES system was coupled to an Applanix Wavemaster POS
136 MV position and data recorder and dual Trimble DGPS receiver system to
137 account for lateral and vertical movement of the vessel. Surface and water
138 column sound velocity values were obtained using Reson SVP71 and SVP15T
139 profilers, respectively. Tidal adjustment was applied from recorded vertical
140 movement of the vessel. Data were collected using a frequency of 240 kHz,
141 and the raw multibeam data was processed using the Teledyne PDS2000 soft-
142 ware package. These data were subsequently corrected for changes in tidal
143 height, water column sound speed, and lateral positioning. Positional data
144 was referenced in the geographical coordinate system WGS84 and projected
145 in Universal Trans Mercator (UTM) Zone 30N. All vertical elevations were
146 reduced to mean sea level (MSL). Following these corrections, the data were
147 exported and converted to a QPS Fledermaus bathymetric file type for de-
148 tailed analysis and visualization. Although the resolution of a multibeam
149 survey is dependent on vessel speed and water depth, typical resolutions
150 achieved from the surveys in Milford Haven ranged from 0.2 to 0.5 m. Ap-
151 proximately 52 km² of seabed in the Milford Haven area was surveyed during
152 two MBES survey programmes in 2013 and 2017, with each survey period
153 typically taking 5 – 10 days to complete.

154 3.2. Tide gauge data

155 The UK National Tide Gauge Network, owned and operated by the Envi-
156 ronment Agency, records tidal elevations at over 40 locations around the UK
157 coast. One of these locations is Milford Haven where a (bubbler³) tide gauge
158 is installed at the seaward end of a concrete jetty (51°42.44’N 05°03.09’W).
159 The data is available from 1953 to present. The time step is 15 minutes from
160 September 1992 to present; older data is at a time step of 1 hour.

²Research, Development and Innovation.

³Also known as a gas purged pressure gauge – a type of water level gauge in which gas is emitted from a submerged orifice at a constant rate. Fluctuations in hydrostatic pressure due to changes in water level modify the recorded emission rate.

161 *3.3. ADCP moorings*

162 *3.3.1. Mean flow properties*

163 The SEACAMS project collected ADCP (acoustic Doppler current pro-
164 filer) data in 2021 to assist Marine Energy Wales in characterizing META.
165 The ADCP deployments at Warrior Way West and Criterion Jetty covered
166 three spring-neap cycles (23 March – 10 May 2021), with the later Warrior
167 Way East deployment (22 April – 10 May 2021) adding an extra datapoint at
168 the Warrior Way test site (Table 2). The 500 kHz Nortek signature ADCPs
169 at Warrior Way were deployed with 1 m bin size, and recorded at a fre-
170 quency of 4 Hz. The RDI sentinel at Criterion Jetty has a slightly higher
171 acoustic frequency (614 kHz), allowing for 0.5 m bins size, but at a slower
172 sampling rate of 2 Hz. All ADCPs were set to measure in bursts of 1024
173 samples, separated by intervals of 30 minutes. Concurrent with the veloc-
174 ity measurements, and at the same sampling rates, all of the instruments
175 recorded pressure, converted into water depth. All ADCPs were deployed on
176 low profile (trawl proof) moorings.

177 *3.3.2. Turbulence measurements*

178 Turbulence measurements were collected at Criterion Jetty (51°41.98'N,
179 4°56.68'W) as part of the testing of a scale prototype of a self recovering
180 instrument frame (an acoustically operated, compressed gas solution designed
181 to house a converging beam acoustic Doppler device that was designed and
182 constructed under the EU ERDF Selkie Project). A Nortek Vector acoustic
183 Doppler velocimeter (ADV) was installed on the frame, which was deployed
184 from 19 May – 4 June 2021, covering one spring-neap cycle. The ADV was
185 positioned such that the measurement volume was 1.15 m above the seabed
186 – higher in the water column than any other parts of the frame, and so
187 relatively undisturbed. Three dimensional (3D) velocity data was collected
188 continuously throughout the deployment at 32 Hz. Post-recovery data was
189 de-spiked based on deviation from a 5-minute rolling average and removing
190 any points that had deviations greater than one standard deviation of the
191 entire record. Turbulent kinetic energy (TKE), k , is then calculated from the
192 variances of the velocity components using:

$$k = \frac{1}{2}(\overline{(u')^2} + \overline{(v')^2} + \overline{(w')^2}) \quad (1)$$

193 Then the turbulent intensity (TI) can be calculated from k and the

194 Reynolds-averaged mean flow U , using:

$$TI = \frac{\sqrt{\frac{2}{3}k}}{U} \quad (2)$$

195 3.4. Wave measurements

196 Wave buoy data was collected at both the Dale Roads wave test site
197 and the East Pickard wave & floating wind site. Data was collected using
198 a Datawell Directional Waverider MkIII, moored in 14 m water depth, at
199 Dale Roads between 2 December 2019 and 14 June 2021 as part of the SEA-
200 CAMS (ERDF) project. Data was collected at East Pickard using an AXYS
201 Technologies Triaxys directional wave buoy, moored in 27 m water depth, be-
202 tween 27 March 2019 and 4 March 2020 – this data was collected by META
203 to support their activities. There is also wave data farther offshore at the
204 Pembrokeshire Demonstration Zone which can be used to consider scaling pa-
205 rameters of the test sites; this data was collected with a Datawell Directional
206 Waverider MkIII. The site was originally run by the SEACAMS project,
207 but since October 2019 the site has been operated by the Cefas Wavenet⁴
208 programme – a UK wave monitoring network.

209 The wave buoys return standard wave parameters (significant wave height,
210 mean, peak and energy (for Dale Roads) wave periods and direction), and
211 one-dimensional wave spectra. The wave energy period is typically used for
212 wave energy characterization; this is not reported for the East Pickard site
213 but can be estimated from the mean period, if a JONSWAP spectrum is
214 assumed [11], using:

$$T_e = 1.18T_z \quad (3)$$

215 Wave power, or wave energy flux, is an important quantity when considering
216 energy extraction. It needs to be calculated from buoy measurements, using:

$$P = EC_g \quad (4)$$

217 where E is the wave energy and C_g is the wave group velocity. The wave
218 energy can be calculated from the wave spectra using

$$E = \rho g m_0 \quad (5)$$

219 where ρ is the seawater density, g is gravity and m_0 is the zeroth spectral
220 moment.

⁴<https://wavenet.cefas.co.uk/>

221 4. META site characterization

222 4.1. Bathymetry

223 4.1.1. Quayside (phase 1) sites

224 Carr Jetty, Mainstay Quay and Ferryside (Fig. 2) are predominantly
225 inter-tidal sites immediately adjacent to deeper water (dredged) areas with
226 depths to 15 m, located 300 m to the south of the main estuary channel. Quay
227 1 is an inter-tidal site to the south of the main estuary channel adjacent to
228 a sloping seabed increasing in depth from 9 – 15 m over a distance of 180
229 m towards the NW. Criterion Jetty lies adjacent to a deep-water channel
230 feature (depth 25 – 28 m) within the main estuary.

231 4.1.2. Open Water (phase 2) sites

232 Warrior Way (Fig. 2, Fig. 3) is situated in the main estuary channel
233 to the east of the Cleddau Bridge and orientated NW-SE with water depths
234 generally in the range 16 – 18 m. Maximum water depths of 22 m are
235 located to the southeast, adjacent to the shallowest region (9 m) located
236 to the northeast of the site where the estuary orientation turns SW-NE.
237 Much of the seabed comprising the northern side of the East Pickard Bay
238 (Fig. 4) to the east of the estuary entrance is characterized by the presence
239 of a N-S and E-W sloping, strongly faulted, bedrock shelf extending 350
240 m south and parallel to the coastline at depths ranging between 8 m and
241 20 m. The bedrock shelf terminates abruptly giving rise to an adjacent area
242 characterized by an E-W gently sloping seabed surface with depths extending
243 from 12 m at the northern end of Freshwater West to 26 m, 2400 m to the
244 west, approximately 1 km south of Whitedole Bay. The Dale Roads site (Fig.
245 5) is characterized by a gentle southerly sloping seabed, with depths ranging
246 from 12 – 15 m over a distance of approximately 600 m. The southwest
247 section of the site is characterized by a 150 m wide, irregular bedrock outcrop
248 extending over 500 m, orientated NW-SE with isolated high points up to 8 m.
249 The seabed surrounding this outcrop appears relatively featureless with no
250 sedimentary bedforms present. Multibeam data from the area further south
251 and west suggests that the vertical extent of seabed sediments throughout
252 this region of the Haven are limited or absent due to the proximity of the
253 underlying bedrock relative to the seabed surface.

254 4.2. Tidal elevations

255 From the 70 year elevation dataset recorded at Milford Haven, the max-
256 imum continuous record was 14 February 2001 to 27 July 2003 (893 days).

257 This time series (with a time step of 15 minutes) was harmonically analyzed
258 using *t_tide* [12] and the tidal constituents with amplitude greater than 5
259 cm are listed in Table 3. Although the Solar annual constituent (SA) was
260 calculated as around 6.4 cm, it was associated with a relatively large error
261 in the harmonic analysis and so is not included in Table 3.

262 The tides are strongly semi-diurnal, with an M2 (S2) amplitude of 2.203
263 m (0.801 m) and a Form Factor⁵ of 0.044. Spring/mean/neap tidal ranges
264 are around 6.3/4.4/2.7 m. The tidal elevations are also characterized by
265 strong lunisolar (K2) and larger lunar elliptic (N2) semidiurnal constituents,
266 leading to relatively large variations in successive spring/neap cycles. This
267 has implications in the time period used for measurements or technology
268 testing as there will be significant differences in spring tides (for example)
269 every two weeks.

270 4.3. Mean flow conditions

271 4.3.1. Depth-averaged currents

272 At Warrior Way East, the 19 day time series shows peak (depth-averaged)
273 current speeds of around 1 m/s (Fig. 6). There is strong flood/ebb asym-
274 metry in the tidal currents, with a typical spring ebb current of 1 m/s being
275 followed by a typical flood current of 0.8 m/s. Tidal analysis of the currents
276 (Table 4) shows that this asymmetry is due to shallow water constituents
277 (at both fourth and sixth diurnal frequencies) at Warrior Way East, and at
278 the other two ADCP locations. The longer (47 day⁶) deployment at Warrior
279 Way West captured multiple spring-neap cycles (Fig. 7). This site is more
280 energetic than Warrior Way East, with peak spring current speeds up to 1.4
281 m/s. Again, there is strong asymmetry in the tidal currents. A peak ebb cur-
282 rent speed of 1.4 m/s is followed by a peak flood current speed of around 0.8
283 m/s. By converting the currents into power, this results in large differences
284 in peak power densities of 1400 kW/m² (ebb) followed by 262 kW/m² (flood)
285 (since the current speed is cubed), i.e. a factor of five. The longer time series
286 also demonstrates that there are large differences in current speeds between
287 successive spring-neap cycles; for example the peak ebb spring current speed
288 is around 1.2 m/s on the 13 April, but exceeds 1.4 m/s on the 28 April. The
289 source of this variation can be attributed to the large N2 current amplitude

⁵Ratio of (K1+O1) to (M2+S2) amplitudes.

⁶Although only 28 days of this time series was usable due to a shift in the mooring

290 at this location (0.154 m/s), which is approximately 50% of the S2 amplitude
 291 (Table 4). Criterion Jetty is much less energetic than the other sites, with
 292 peak currents of around 0.6 m/s (Fig. 8). The depth-averaged currents for
 293 all three locations are compared as ‘tidal ellipses’ in Fig. 9, confirming the
 294 strong magnitude asymmetry between the flood and ebb phases of the tidal
 295 cycle, yet associated with minimal directional asymmetry.

296 4.3.2. Depth-varying currents

297 The three ADCP deployments (Table 2) allow the hydrodynamics to be
 298 analyzed throughout the water-column (except near surface and near seabed)
 299 and quantified through harmonic analysis. Harmonic analysis was performed
 300 using least-squares fitting *t_tide* package ([12]) on the north-south (*v*) and
 301 east-west (*u*) components of depth-averaged current and the current time-
 302 series at each “bin” (ensemble-averaged height above the seabed: see Table
 303 2). The time-series figures of observed currents, in depth and time, are shown
 304 in Fig. 10, Fig. 11, and Fig. 12, for Warrior Way East, Warrior Way West,
 305 and Criterion Jetty, respectively.

306 The time-series (top panel in Fig. 10, Fig. 11, and Fig. 12) was harmon-
 307 ically analyzed, with “non-harmonic flow”, i.e. any residual currents remain-
 308 ing that could not be accounted with harmonics, given an error in both
 309 time (summed throughout the water-column) and throughout the water-
 310 column (summed through time) calculated. Near-surface bins, where data
 311 was missing due to the tidal range introducing gaps in the tidal current time-
 312 series, were removed from the analysis – further reducing the amount of data,
 313 but necessary due to the increasing error (σ_{RMSE}) near the surface. At all
 314 three sites, no correlation to error (or non-harmonic “weather” flows) was
 315 found – for example with observed wind speed at the port of Milford Haven
 316 ($R^2 < 1\%$). Instead, the non-harmonic flow is likely to be due to unresolved
 317 harmonic features within the tide: as can be seen by the regular periodicity
 318 in the time-series error of Fig. 10.

319 Further characterization of the tidal flow was performed at the three
 320 ADCP sites by grouping data into “flooding” (tidal currents from Low Water
 321 to High Water) and “ebbing” (tidal currents from High Water to Low Water);
 322 as described in Lewis et al. [13], assuming a standing wave system. All sites
 323 have near-rectilinear flow conditions, and flood-ebb asymmetry is in current
 324 magnitude only (Fig. 9). Further analysis, with the curve fitting profile
 325 described in Lewis et al. [13], shows that the velocity profiles have minimal
 326 shear at these sites, with near plug flow ($\sim 1/14$ th power law) instead of

327 1/7th power law found in more “open coastal” tidal energy sites as shown
 328 in Table 5; where the velocity at a specific height above bed (U_z) can be
 329 described using the depth-averaged flow (\bar{U}), water depth, and the power
 330 (α) and roughness (β) coefficients:

$$U_z = \left(\frac{z}{\beta h} \right)^{1/\alpha} \bar{U} \quad (6)$$

331 Therefore, we find tidal flows at Warrior Way and Criterion Jetty are heav-
 332 ily modified by friction, with flood-ebb asymmetry in current magnitude and
 333 velocity profile shape – suggesting seabed feature generated effects are influ-
 334 encing flow conditions (e.g. Fig. 3). Indeed, Criterion Jetty showed much
 335 greater variability and difference between the flood and ebb tides, whilst
 336 Warrior Way had a similar pattern on either side and, relatively, lower vari-
 337 ability in space and time (see Fig. 13) – hence Warrior Way appears to have
 338 favourable conditions for hydrokinetic energy device deployments.

339 4.4. Turbulence properties

340 Turbulent Kinetic Energy (TKE) for Criterion Jetty is plotted against
 341 mean velocity (Fig. 14), with a clear, if unsurprising, trend of TKE increasing
 342 with increasing mean velocity. Turbulence Intensity (TI) is shown in Fig.
 343 15. There is greater variability at lower velocities, and there are higher TI
 344 values associated with lower mean velocities due to mean velocity being the
 345 denominator in Eq. 2, similar to other studies, e.g. [14]. The mean value for
 346 TI is 0.55 or 55%, which is high compared to many tidal stream sites, where
 347 values of 5 – 35% have been reported [15, 16, 17]. This may be due to the
 348 generally low mean velocities at Criterion Jetty (e.g. peak spring current of
 349 0.6 m/s) compared to grid-connected commercial sites where current speeds
 350 are often in excess of 2.5 m/s [18]. On the flood phase of the tidal cycle,
 351 there are minimal bed features upstream, and so turbulence is bed-generated.
 352 On the ebb phase of the tidal cycle, there is a large meandering channel
 353 and bridge pilings 1 km upstream, all of which may generate additional
 354 turbulence. Given the shallow water depths at Criterion Jetty, minimal depth
 355 variation in turbulence is expected.

356 4.5. Wave climate

357 Wave roses were calculated for both wave energy test sites (Fig. 16).
 358 Wave heights are greater at the more exposed East Pickard site, and there

359 is greater variability (compared to Dale Roads) about the predominant wave
360 direction (from the WSW). Refraction into the Milford Haven Estuary means
361 that waves at Dale Roads are predominantly incident from the SSW. Joint
362 $H_s - T_e$ occurrence matrices are shown for Dale Roads (Fig. 17) and East
363 Pickard (Fig. 18). Fig. 19 displays time series of wave power at the two
364 sites. Time periods are not concurrent, but similar seasonality can be seen
365 at both sites with typically higher values in the winter months; however, it
366 should be noted that energetic storms can occur at any time of year. Mean
367 values of key parameters for both sites are summarized in Table 6.

368 One of the benefits of the META suite of test locations is the proximity
369 to the PDZ (see Section 1). Therefore it is instructive to consider the scal-
370 ing factors between both Dale Roads & East Pickard and the PDZ. Based
371 on Froude scaling, wave heights scale linearly, and comparison can be used
372 to identify the scale factor between sites. For perfect scaling, wave heights
373 should then scale by the square root of the scale factor. Given the influ-
374 ence of water depth on wave characteristics, site water depth should also
375 scale linearly with the wave height scale factor. In this section, line fitting
376 to scatter plots is used to establish scale factors. Due to data availability,
377 scaling estimates are made for different time periods for both test sites: for
378 Dale Roads, a year of data between 01/02/2020 and 31/01/2021 was used;
379 however for East Pickard, larger data gaps meant comparison was made be-
380 tween 15/06/2019 – 14/10/2019, 22/10/2019 – 06/11/2019, and 23/01/2020
381 – 03/04/2020.

382 Fig. 20 shows scatter plots for various parameters at Dale Roads and the
383 PDZ; lines of best fit of the form $y = mx$ are plotted for each parameter.
384 Forcing the intercept to zero allows the gradient to equal the scale factor.
385 This gives a scale factor of 0.31, or approximately 1/3 between Dale Roads
386 and the PDZ. Based on Froude scaling, the scale factor for the wave period
387 should be 0.56; in fact, the gradient is 0.82 for the mean period and 0.95
388 for peak periods. Energy period is not shown, because measured values are
389 not available for East Pickard or for the PDZ data collected by Cefas. It is
390 unsurprising that peak periods are so similar, given the close proximity of the
391 two buoys and the fact that while energy may be redistributed due to wave
392 transformation processes, peak period is unlikely to be altered. Differences in
393 scale factor between wave height and period is something that has been noted
394 at other real-world scale test sites. Directional spreading is slightly lower at
395 the Dale Roads site, presumably due to its more constrained location. The
396 scale factor between water depths at the two sites is 0.25 (14 m at Dale Roads,

397 56 m at PDZ). This means that water depths and wave heights have similar
398 scaling and so, despite the less satisfactory wave period scaling, Dale Roads
399 can be considered a scale site for the PDZ with a scale factor of 1/3. When
400 the same plot is created for the comparison between East Pickard and the
401 PDZ, it can be seen that the wave climate at both sites is very similar. While
402 East Pickard is further inshore and in shallower water, it is just as exposed
403 to the predominant SW and W wave incidence as the PDZ. Therefore the
404 scaling of waves is 0.8, and both mean and peak period scaling is > 0.95 .
405 This means East Pickard is not a useful scale site for the PDZ, but should
406 be considered as a scale site for more energetic areas or as a useful location
407 for nearshore full scale testing prior to deployment at the PDZ.

408 5. Discussion

409 *The META data*

410 The primary tidal test site (Warrior Way) has water depths in the range
411 10 – 20 m, suitable for testing TRL 4–6. However, it should be noted that a
412 spring tidal range of 6.3 m could present a challenge for some devices (e.g. at
413 the shallower end of Warrior Way total water depth will vary between 7–13 m
414 during a spring tide), and could favour testing of floating technologies. This
415 is in contrast to EMEC, where the tidal range is around 2.3 m (spring) [19].
416 The sea bed at the more exposed wave test sites is generally characterized as
417 bed rock, much in agreement with any other high energy wave energy test or
418 commercial sites (e.g. [20]). All investigated sites within the Milford Haven
419 waterway were strongly asymmetrical due to shallow water harmonics at
420 fourth and sixth diurnal frequencies. Since power is proportional to velocity
421 cubed, this asymmetry is amplified in power output, but the Fall of Warness
422 in Orkney is also an example of an asymmetrical test site [21], yet has been a
423 successful test location over the last 15 years. This would not be the case at
424 a commercial site, where asymmetry in power output would be undesirable.
425 Examination of how the current speed varies over the water column shows
426 minimal shear at these sites, with near plug flow ($\sim 1/14$ th power law)
427 instead of the classical $1/7$ th power law commonly found at other tidal energy
428 test locations (e.g. [22]). Turbulence intensities are higher at the Criterion
429 Way site (55%) than is often reported in the literature for prospective tidal
430 stream energy sites, which are typically 5–35% [15, 16, 17]. This finding will
431 be important for developers to consider when conducting early stage tests at

432 this location, because turbulence induced stresses would be proportionally
433 greater than at full-scale.

434 The wave climate and water depths at the Dale Road site provide a good
435 1/3 scale test site for the neighbouring Pembrokeshire Demonstration Zone
436 (PDZ). Conditions at the East Pickard location are similar to the PDZ, with
437 a wave height scale factor of 4/5. Therefore, this site is better considered as
438 a scale site for more energetic locations. Given that East Pickard is *en route*
439 from Milford Haven to the PDZ, it may prove a useful site for short-term
440 full-scale testing prior to deployment of devices at the PDZ.

441 *Additional data collection*

442 The data collected from META is already extensive, particularly the
443 multibeam data coverage, but further data would be useful in characterizing
444 the site both spatially and temporally.

445 Further multibeam surveys would provide complete coverage across the
446 sites, and such data would also assist in parameterizing model bathymetry
447 (see next sub-section). Also, many regions of the Milford Haven waterway are
448 dredged, and up-to-date multibeam surveys would help characterize changes
449 in the sea bed over time.

450 The three ADCP moorings presented here offer a robust initial overview of
451 tidal dynamics across META, but further deployments at multiple locations,
452 and covering different time periods will further refine the site characteriza-
453 tion. It has been noted that nodal corrections over an 18.6 year cycle can lead
454 to an error exceeding $\pm 10\%$ in annual energy yield (AEY) depending on the
455 year selected for data collection [23], and so repeat surveys, even at the same
456 locations, can be useful in further quantifying and characterizing the tidal
457 energy resource, including resolving additional tidal constituents than those
458 presented here (Table 4). In addition to point sensors, further spatial surveys
459 in the region to characterize the currents could include ADCP transects [24]
460 and novel methods of data collection such as drone-based large-scale parti-
461 cle image velocimetry [25] and X-band radar [8]. Further information about
462 turbulent properties at the other tidal test locations in the META suite of
463 facilities (i.e. beyond the low energy Criterion Jetty site) would be bene-
464 ficial to developers. A converging beam ADCP array (comprised of three
465 ADCPs), specifically built for improved turbulence measurements at tidal
466 energy sites, has recently been deployed at the Warrior Way site as part of
467 the Selkie Project, and tests are underway.

468 *Numerical model development*

469 The evidence presented in this paper is based entirely on *in situ* data.
470 Although wave properties, and to a lesser extent tidal properties, will change
471 over longer timescales⁷, it is also useful to use numerical models to simulate
472 the waves and tides of the region, e.g. to investigate scenarios that have
473 not necessarily been captured by the observations (e.g. extreme events), and
474 also to provide consistent spatial and temporal coverage of the region. Such a
475 model (or series of models) could be parameterized and calibrated/validated
476 by the data presented in this study. Since models are often validated out-
477 side of the region of interest, providing confidence in the wave/tidal proper-
478 ties throughout the computational domain, they can be used to investigate
479 near-field and far-field environmental impacts, including feedbacks between
480 devices and the resource.

481 *Future of META*

482 At the time of writing, META has been fully operational for 1 year and
483 has started to develop a project pipeline. The types of experimental devices
484 that are planned to test at META in the near-to-medium future include
485 tidal turbines, wave energy convertors, offshore hydrogen systems, and vari-
486 ous novel sub-assemblies, components, and scientific instruments. Since the
487 META initiative was conceived in 2017, the offshore renewables industry has
488 evolved, with increased interest in testing floating offshore wind, hydrogen,
489 floating solar, hybrid and co-located systems, and automated and robotic
490 systems. In turn, the META facility will primarily continue to support wave
491 and tidal technology testing, but where possible expand its offering to accom-
492 modate these other marine technologies which have a role in the renewable
493 energy transition. This may involve varying consents at existing sites, or
494 developing new sites in and around the Milford Haven Waterway.

495 Some important objectives for META to ensure future success are to
496 continue adding value to the facility in terms of data, infrastructure, and
497 equipment availability; an ability to adapt to meet diverse marine technology
498 requirements; and to pursue collaboration with existing and new partners to
499 create a hub for research, development and innovation around the META
500 facility.

⁷E.g. due to sea-level rise/climate change or inter-annual variability.

501 **6. Conclusion**

502 This article has presented analysis and synthesis of the various datasets
503 that have been collected from the META sites over the past decade. The
504 results demonstrate the opportunities and challenges associated with testing
505 at META, e.g. strong asymmetry in the tides. We have highlighted gaps in
506 data from both spatial and temporal perspectives, and how future data col-
507 lection, and the development of a numerical model of the region, will support
508 wave and tidal technology testing, in addition to providing the flexibility to
509 expand into testing other marine energy technologies such as floating wind
510 and solar, and co-located devices.

511 **Acknowledgements**

512 The Bangor University researchers acknowledge the support of the Smart
513 Efficient Energy Centre (SEEC), and SEACAMS I, II, all projects funded
514 by the Welsh European Funding Office (WEFO) as part of the European
515 Regional Development Fund (ERDF). The researchers at Swansea University
516 also acknowledge the support of SEACAMS I, II, in addition to Selkie, a
517 project that was funded by the ERDF through the Ireland-Wales Cooperation
518 programme.

519 **Data availability**

520 The multibeam and ADCP data are available from the IMARDIS data
521 portal <https://portal.imardis.org/>. The wave data for Dales Roads is
522 available from Cefas WaveNet [https://www.cefas.co.uk/data-and-publications/
523 wavenet/](https://www.cefas.co.uk/data-and-publications/wavenet/), and the East Pickard wave data is available upon reasonable re-
524 quest from Marine Energy Wales. The tide gauge data are available from
525 the British Oceanographic Data Centre (BODC) [https://www.bodc.ac.uk/
526 data/hosted_data_systems/sea_level/uk_tide_gauge_network/](https://www.bodc.ac.uk/data/hosted_data_systems/sea_level/uk_tide_gauge_network/)

527 **References**

- 528 [1] V. Marti, J. Culina, S. Neill, Ocean renewable energy test centers, in:
529 Comprehensive Renewable Energy, 2022.
- 530 [2] B. Gaurier, G. Germain, J.-V. Facq, C. Johnstone, A. Grant, A. Day,
531 E. Nixon, F. Di Felice, M. Costanzo, Tidal energy “Round Robin” tests
532 comparisons between towing tank and circulating tank results, Internation-
533 al Journal of Marine Energy 12 (2015) 87–109.
- 534 [3] R. Yemm, D. Pizer, C. Retzler, R. Henderson, Pelamis: experience from
535 concept to connection, Philosophical Transactions of the Royal Society
536 A: Mathematical, Physical and Engineering Sciences 370 (1959) (2012)
537 365–380.
- 538 [4] M. Lewis, R. O. Murray, S. Fredriksson, J. Maskell, A. de Fockert, S. P.
539 Neill, P. E. Robins, A standardised tidal-stream power curve, optimised
540 for the global resource, Renewable Energy 170 (2021) 1308–1323.
- 541 [5] M. Piano, S. Ward, P. Robins, S. Neill, M. Lewis, A. Davies, B. Powell,
542 A. W. Owen, R. Hashemi, Characterizing the tidal energy resource of the
543 west Anglesey Demonstration Zone (UK), using Telemac-2D and field
544 observations, in: Proceedings of the XXII TELEMAC-MASCARET
545 Technical User Conference October 15-16, 2042, 2015, pp. 195–203.
- 546 [6] R. Roche, K. Walker-Springett, P. Robins, J. Jones, G. Veneruso,
547 T. Whitton, M. Piano, S. Ward, C. Duce, J. Waggitt, et al., Research
548 priorities for assessing potential impacts of emerging marine renewable
549 energy technologies: Insights from developments in Wales (UK), Re-
550 newable Energy 99 (2016) 1327–1341.

- 551 [7] S. P. Neill, M. J. Lewis, M. R. Hashemi, E. Slater, J. Lawrence, S. A.
552 Spall, Inter-annual and inter-seasonal variability of the Orkney wave
553 power resource, *Applied Energy* 132 (2014) 339–348.
- 554 [8] S. P. Neill, K. A. Haas, J. Thiébot, Z. Yang, A review of tidal energy–
555 resource, feedbacks, and environmental interactions, *Journal of Renew-
556 able and Sustainable Energy* 13 (6) (2021) 062702.
- 557 [9] A. Sentchev, M. Thiébaud, F. G. Schmitt, Impact of turbulence on power
558 production by a free-stream tidal turbine in real sea conditions, *Renew-
559 able Energy* 147 (2020) 1932–1940.
- 560 [10] T. Blackmore, L. E. Myers, A. S. Bahaj, Effects of turbulence on tidal
561 turbines: Implications to performance, blade loads, and condition mon-
562 itoring, *International Journal of Marine Energy* 14 (2016) 1–26.
- 563 [11] B. Cahill, T. Lewis, Wave period ratios and the calculation of wave
564 power, in: *METS2014*, 2014.
- 565 [12] R. Pawlowicz, B. Beardsley, S. Lentz, Classical tidal harmonic analy-
566 sis including error estimates in MATLAB using T.TIDE, *Computers &
567 Geosciences* 28 (8) (2002) 929–937.
- 568 [13] M. Lewis, S. Neill, P. Robins, M. R. Hashemi, S. Ward, Characteristics
569 of the velocity profile at tidal-stream energy sites, *Renewable Energy*
570 114 (2017) 258–272.
- 571 [14] N. S. Lucas, M. J. Austin, T. P. Rippeth, B. Powell, P. Wakonigg,
572 Turbulence and coherent structure characterisation in a tidally energetic
573 channel, *Renewable Energy* 194 (2022) 259–272.
- 574 [15] P. Garcia Novo, Y. Kyojuka, Analysis of turbulence and extreme cur-
575 rent velocity values in a tidal channel, *Journal of Marine Science and
576 Technology* 24 (3) (2019) 659–672.
- 577 [16] I. A. Milne, R. N. Sharma, R. G. Flay, S. Bickerton, Characteristics
578 of the turbulence in the flow at a tidal stream power site, *Philosophical
579 Transactions of the Royal Society A: Mathematical, Physical and
580 Engineering Sciences* 371 (1985) (2013) 20120196.

- 581 [17] M. Togneri, I. Masters, Micrositing variability and mean flow scaling for
582 marine turbulence in Ramsey Sound, *Journal of Ocean Engineering and*
583 *Marine Energy* 2 (1) (2016) 35–46.
- 584 [18] D. Coles, A. Angeloudis, D. Greaves, G. Hastie, M. Lewis, L. Mackie,
585 J. McNaughton, J. Miles, S. Neill, M. Piggott, et al., A review of the
586 UK and British Channel Islands practical tidal stream energy resource,
587 *Proceedings of the Royal Society A* 477 (2255) (2021) 20210469.
- 588 [19] S. P. Neill, A. Vögler, A. J. Goward-Brown, S. Baston, M. J. Lewis, P. A.
589 Gillibrand, S. Waldman, D. K. Woolf, The wave and tidal resource of
590 Scotland, *Renewable Energy* 114 (2017) 3–17.
- 591 [20] EMEC, Billia Croo test site: Environmental statement (2019).
- 592 [21] S. P. Neill, M. R. Hashemi, M. J. Lewis, The role of tidal asymmetry in
593 characterizing the tidal energy resource of Orkney, *Renewable Energy*
594 68 (2014) 337–350.
- 595 [22] M. Thiébaud, A. Sentchev, Asymmetry of tidal currents off the W. Brit-
596 tany coast and assessment of tidal energy resource around the Ushant
597 Island, *Renewable Energy* 105 (2017) 735–747.
- 598 [23] K. Haas, T. Xu, B. Gunawan, Evaluating measurement based tidal en-
599 ergy resource assessment methods, 2022 Ocean Sciences Meeting (2022).
- 600 [24] S. Neill, A. Elliott, In situ measurements of spring–neap variations to
601 unsteady island wake development in the Firth of Forth, Scotland, *Es-
602 tuarine, Coastal and Shelf Science* 60 (2) (2004) 229–239.
- 603 [25] I. Fairley, B. J. Williamson, J. McIlvenny, N. King, I. Masters, M. Lewis,
604 S. Neill, D. Glasby, D. Coles, B. Powell, et al., Drone-based large-scale
605 particle image velocimetry applied to tidal stream energy resource as-
606 sessment, *Renewable Energy* 196 (2022) 839–855.
- 607 [26] R. Soulsby, *Dynamics of Marine Sands* (1997).

608 **Figure Captions**

609 **Fig. 1** META test areas in the Milford Haven Waterway and surrounding
610 waters. Quayside (phase 1) sites in orange, open water (phase 2) sites in
611 green. Red lines in (a) are electricity transmission lines. Data from the
612 Ordnance Survey and META.

613 **Fig. 2** Multibeam echosounder bathymetry of Pembroke Dock and War-
614 rior Way. Water depths (in metres) relative to mean sea level. Symbols rep-
615 resent the locations of the ADCP moorings – Criterion Jetty (black square),
616 Warrior Way West (black triangle), and Warrior Way East (black circle).
617 White outlines show the test areas.

618 **Fig. 3** Multibeam echosounder bathymetry of Warrior Way (tidal test
619 site – shown as a white outline). Water depths (in metres) relative to mean
620 sea level. Symbols represent the locations of the ADCP moorings – War-
621 rior Way West (black triangle) and Warrior Way East (black circle). White
622 outlines show the test areas.

623 **Fig. 4** Multibeam echosounder bathymetry of East Pickard Bay (wave &
624 floating wind test site – shown as a white outline). Water depths (in metres)
625 relative to mean sea level.

626 **Fig. 5** Multibeam echosounder bathymetry of Dale Roads (wave test site
627 – shown as a white box). Water depths in metres relative to mean sea level.

628 **Fig. 6** Time series of water surface elevations and depth-averaged current
629 speed at Warrior Way East, 22 April – 10 May 2021.

630 **Fig. 7** Time series of water surface elevations, depth-averaged current
631 speed, and power density at Warrior Way West, 31 March – 29 April 2021.
632 Note that the Warrior Way West mooring shifted during the deployment,
633 and so only 28 days of data (out of the full 47 day record) were used for
634 analysis.

635 **Fig. 8** Time series of depth-averaged current speed at Criterion Jetty, 23
636 March – 10 May 2021. Difference in successive spring currents (at fortnightly
637 intervals) is mainly due to the N2 tidal constituent, which has a magnitude
638 of 20% and 50% of the M2 and S2 constituents, respectively (Table 4).

639 **Fig. 9** Depth-averaged current ellipses.

640 **Fig. 10** ADCP data time-series at Warrior Way East with surface-
641 affected data removed. (a) is observed current magnitude (m/s), and (b)
642 is the non-harmonic flow (as a percentage of (a)), where the predicted tidal
643 currents (from harmonic analysis) are subtracted from the observed currents.
644 The residual “error” is shown in (c), summed throughout the water-column,

645 and (d) is the wind speed at Milford Haven. (e) is the time-averaged “er-
646 ror” through the water-column, and (f) shows the relationship between wind
647 speed and residual error summed through the water column.

648 **Fig. 11** ADCP data time-series at Warrior Way West with surface-
649 affected data removed. (a) is observed current magnitude (m/s), and (b)
650 is the non-harmonic flow (as a percentage of (a)), where the predicted tidal
651 currents (from harmonic analysis) are subtracted from the observed currents.
652 The residual “error” is shown in (c), summed throughout the water-column,
653 and (d) is the wind speed at Milford Haven. (e) is the time-averaged “error”
654 through the water-column, and (f) shows the relationship between wind speed
655 and residual error summed through the water column.

656 **Fig. 12** ADCP data time-series at Criterion Jetty with surface-affected
657 data removed. (a) is observed current magnitude (m/s), and (b) is the non-
658 harmonic flow (as a percentage of (a)), where the predicted tidal currents
659 (from harmonic analysis) are subtracted from the observed currents. The
660 residual “error” is shown in (c), summed throughout the water-column, and
661 (d) is the wind speed at Milford Haven. (e) is the time-averaged “error”
662 through the water-column, and (f) shows the relationship between wind speed
663 and residual error summed through the water column.

664 **Fig. 13** Velocity profile fits at each of the ADCP locations: (a) Warrior
665 way East, (b) Warrior Way West, and (c) Criterion Jetty. The light grey
666 lines show the instantaneous fits, and the dark solid lines are the averaged
667 fits for flood (red) and ebb (blue). Dashed lines are one standard deviation
668 either side of this mean. Where there was little variability in the shape and
669 magnitude of the velocity profile, the standard deviation associated with the
670 mean is close together. Sites with little vertical shear in velocity, with little
671 variation in the flow speed at depth or near the surface, have a straighter
672 vertical line.

673 **Fig. 14** The relationship between mean current speed and Turbulent
674 Kinetic Energy at Criterion Jetty ($51^{\circ}41.98'N$ $04^{\circ}56.68'W$).

675 **Fig. 15** The relationship between mean current speed and Turbulence
676 Intensity at Criterion Jetty.

677 **Fig. 16** Wave roses for East Pickard (left) and Dale Roads (right) based
678 on one year of data at each location (from 03/2019 for East Pickard and
679 12/2019 for Dale Roads).

680 **Fig. 17** A significant wave height – energy period joint occurrence matrix
681 for one year (2020) of wave data at Dale Roads.

682 **Fig. 18** A significant wave height – energy period joint occurrence matrix

683 for the East Pickard dataset.

684 **Fig. 19** Time series of wave power for: (a) Dale Roads, and (b) East
685 Pickard.

686 **Fig. 20** Scatter plots of wave parameters for Dale Roads (DR) and
687 the Pembrokeshire demonstration zone (PDZ). Scatter is shaded such that
688 yellows indicate denser regions in the scatter plots. Lines of best fit, of the
689 form $y = mx$, are given as black dashed lines, the gradient of these indicate
690 the scale factor

691 **Tables (including captions)**

Category	Site name
Quayside (phase 1) sites	Carr Jetty Mainstay Quay Ferryside Quay 1 Criterion Jetty
Open water (phase 2) sites	Warrior way (tidal) Dale Roads (wave) East Pickard Bay (wave & floating wind)

Table 1: List of the META Quayside and Open Water test areas.

	Warrior Way East	Warrior Way West	Criterion Jetty
Deployment latitude	51°42.21'N	51°42.10'N	51°41.99'N
Deployment longitude	04°55.63'W	04°55.31'W	04°56.65'W
Recovery latitude	51°42.20'N	51°42.10'N	51°42.00'N
Recovery longitude	04°55.58'W	04°55.26'W	04°56.60'W
Start date	22 April 2021	23 March 2021	23 March 2021
End date	10 May 2021	10 May 2021	10 May 2021
Water depth (m, relative to MSL)	15.1	19.7	20.1
Instrument	Nortek Signature 500	Nortek Signature 500	RDI Sentinel V
Number of beams	5	5	5
Acoustic Frequency (kHz)	500	500	614
Blanking distance (m)	0.5	0.5	1.68
Bin size (m)	1	1	0.5
Number of bins	28	28	58
Sampling frequency (Hz)	4	4	2
Number of samples per burst	1024	1024	1024
Profile interval (s)	600	600	600
Time between bursts (s)	1800	1800	1800

Table 2: Details of the three ADCP moorings and configurations.

Constituent	Name	Period (h)	H (m)	G (deg)
M4	SW overtide of principal lunar constituent	6.21	0.064	306.2
K2	Lunisolar semidiurnal	11.97	0.231	214.7
S2	Principal solar semidiurnal	12.00	0.801	216.8
L2	Smaller lunar elliptic semidiurnal	12.19	0.120	166.4
M2	Principal lunar semidiurnal	12.42	2.203	172.6
NU2	Larger lunar evectional	12.63	0.086	145.4
N2	Larger lunar elliptic semidiurnal	12.66	0.427	152.6
MU2	Variational constituent	12.87	0.077	188.7
2N2	Lunar elliptic semi diurnal second-order	12.91	0.055	135.4
K1	Lunisolar diurnal	23.93	0.066	130.7
O1	Lunar diurnal	25.82	0.066	354.7

Table 3: Tidal constituents (listed in ascending order of their period) with an amplitude greater than 5 cm based on tidal analysis of 893 days of continuous tide gauge data from Milford Haven. H is amplitude (in metres) and G is phase (in degrees relative to Greenwich). SW = Shallow Water.

Constituent	Name	Warrior Way E.	Warrior Way W.	Criterion Jetty
M2	Principal lunar semidiurnal	0.545	0.656	0.252
S2	Principal solar semidiurnal	0.184	0.304	0.111
N2	Larger lunar elliptic semidiurnal	NA	0.154	0.052
M4	Fourth diurnal shallow water const.	0.061	0.087	0.030
MS4	Fourth diurnal shallow water const.	0.040	0.078	0.029
MSF	Lunisolar synodic fortnightly const.	0.009	0.072	0.025
2MS6	Sixth diurnal shallow water const.	0.054	0.054	0.038
M6	Sixth diurnal shallow water const.	0.065	0.038	0.029
2MN6	Sixth diurnal shallow water const.	NA	0.027	0.021

Table 4: Semi major axis (m/s) for dominant depth-averaged tidal constituents, noting that tidal currents are strongly rectilinear at all three sites (Fig. 9). NA = time period of deployment (19 days) too short to resolve this constituent, i.e. to separate it from constituents that are very close in frequency.

Site	β	flood		ebb	
		α	error (%)	α	error (%)
Warrior Way East	0.4	10	15	13	14
Warrior Way West	0.4	14	17	14	5
Criterion Jetty	0.4	15	5	15	5

Table 5: The velocity profile fitting results for ADCP data at the three sites, using a power law relationship (α) of the Soulsby velocity profile fit [26], as described in Lewis et al. [13]. A lower α value denotes a greater amount of vertical shear in the water column.

Site	H_s (m)	T_p (s)	T_e (s)	T_z (s)	Power (kW/m)	Dir. ($^\circ$)	Dir. Spr. ($^\circ$)
Dale Roads	0.57	8.90	6.72	4.55	2.19	196	24.2
East Pickard	1.57	8.88	6.47	5.49	9.42	243	33.40

Table 6: Mean values for significant wave height (H_s), peak period (T_p), energy period (T_e), zero up-crossing period (T_z), wave power (kW/m), peak wave direction and directional spreading.

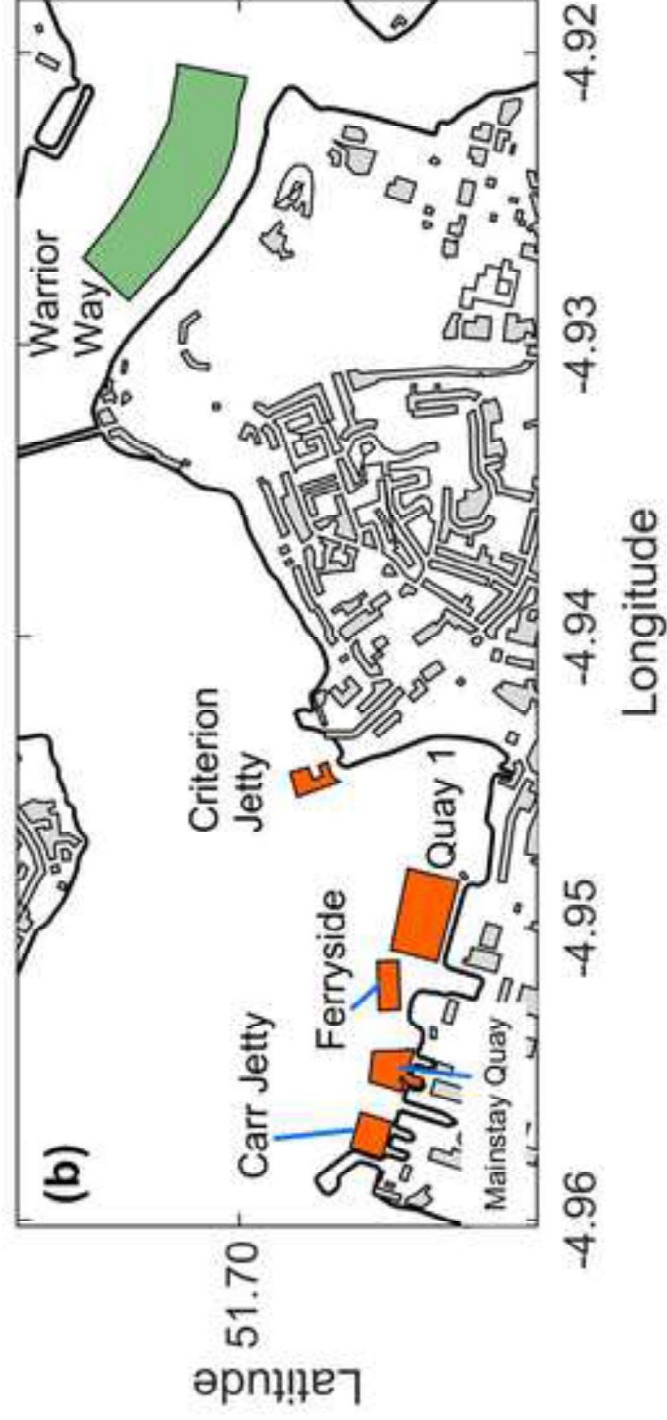
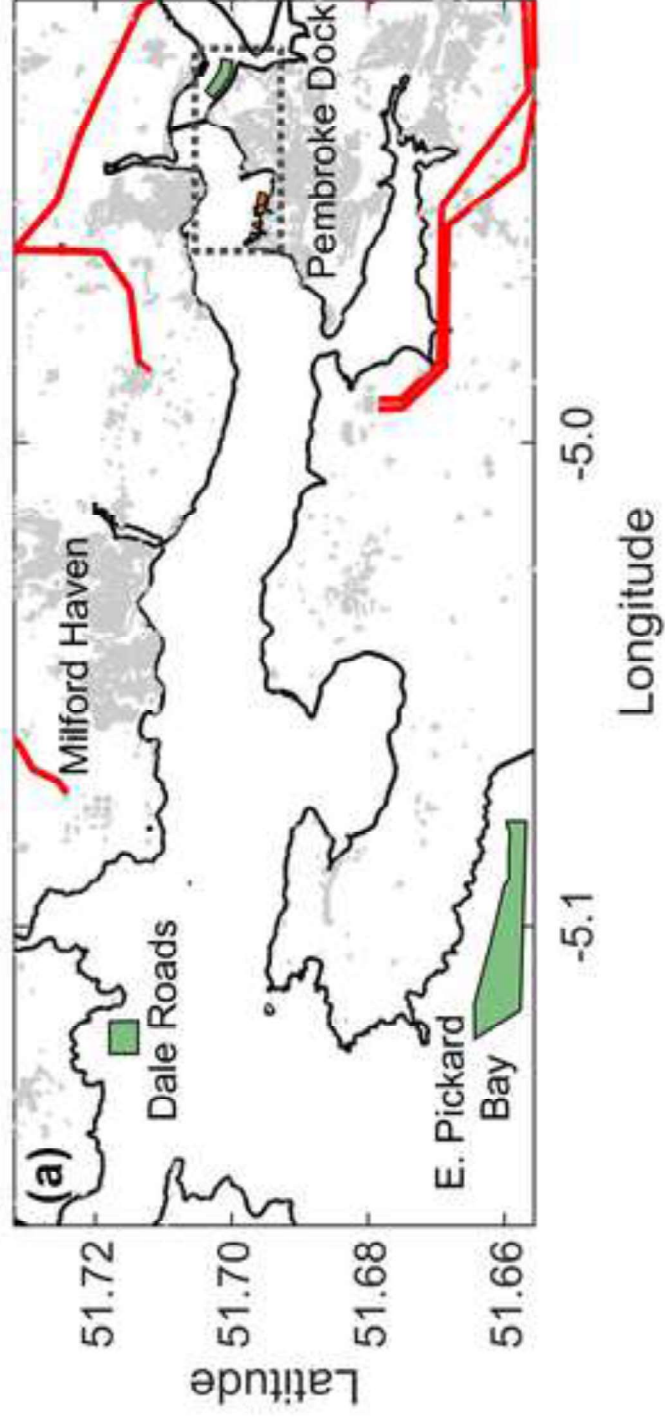
Declaration of interests

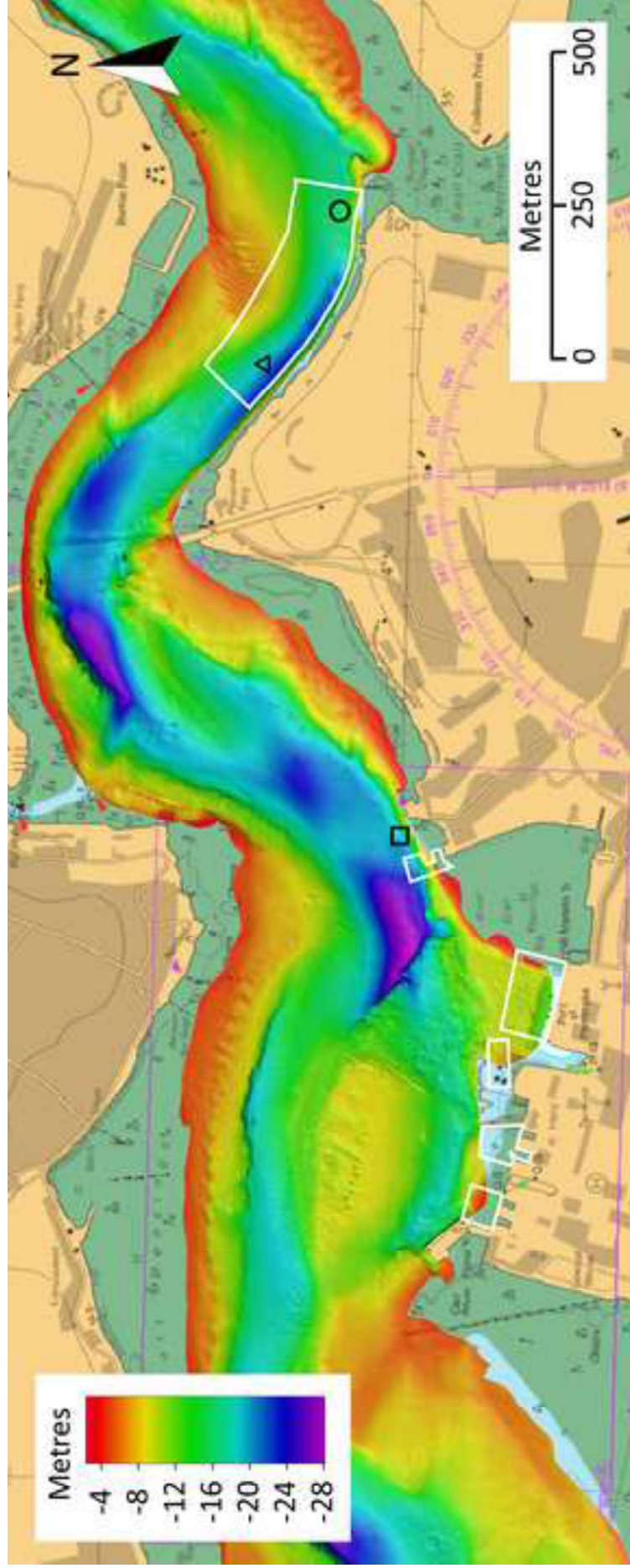
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

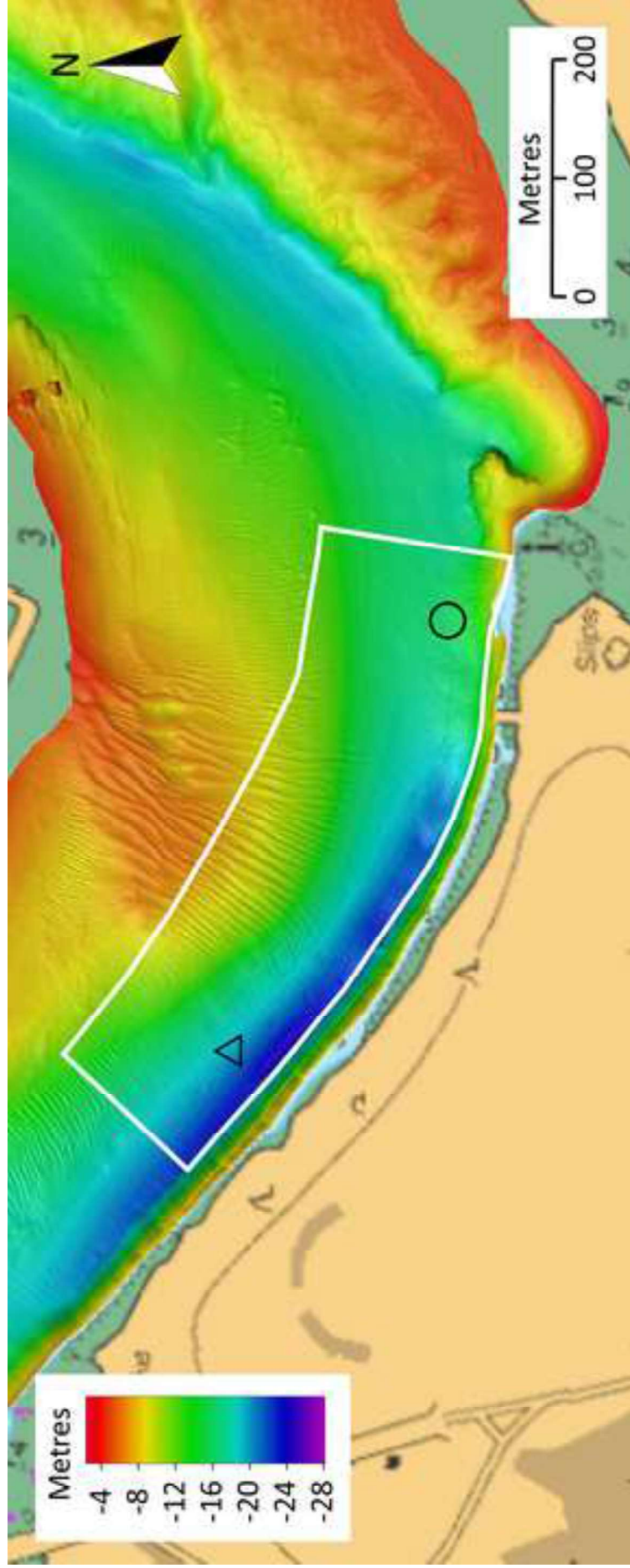
The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

CRedit author statement

Simon P. Neill: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Visualization, Funding acquisition **Iain A. Fairley:** Methodology, Formal analysis, Investigation, Writing - Original Draft, Visualization **Steve Rowlands:** Formal analysis, Visualization **Saul Young:** Writing - Review & Editing **Tom Hill:** Writing - Review & Editing **Christopher A. Unsworth:** Investigation, Writing - Review & Editing **Nicholas King:** Formal analysis, Investigation, Visualization **Michael J. Roberts:** Investigation, Writing - Review & Editing **Martin J. Austin:** Writing - Review & Editing **Peter Hughes:** Investigation **Ian Masters:** Writing - Review & Editing, Funding acquisition **Aled Owen:** Investigation **Ben Powell:** Investigation **Dominic Reeve:** Funding acquisition **Matthew J. Lewis:** Formal analysis, Writing – Original Draft, Visualization







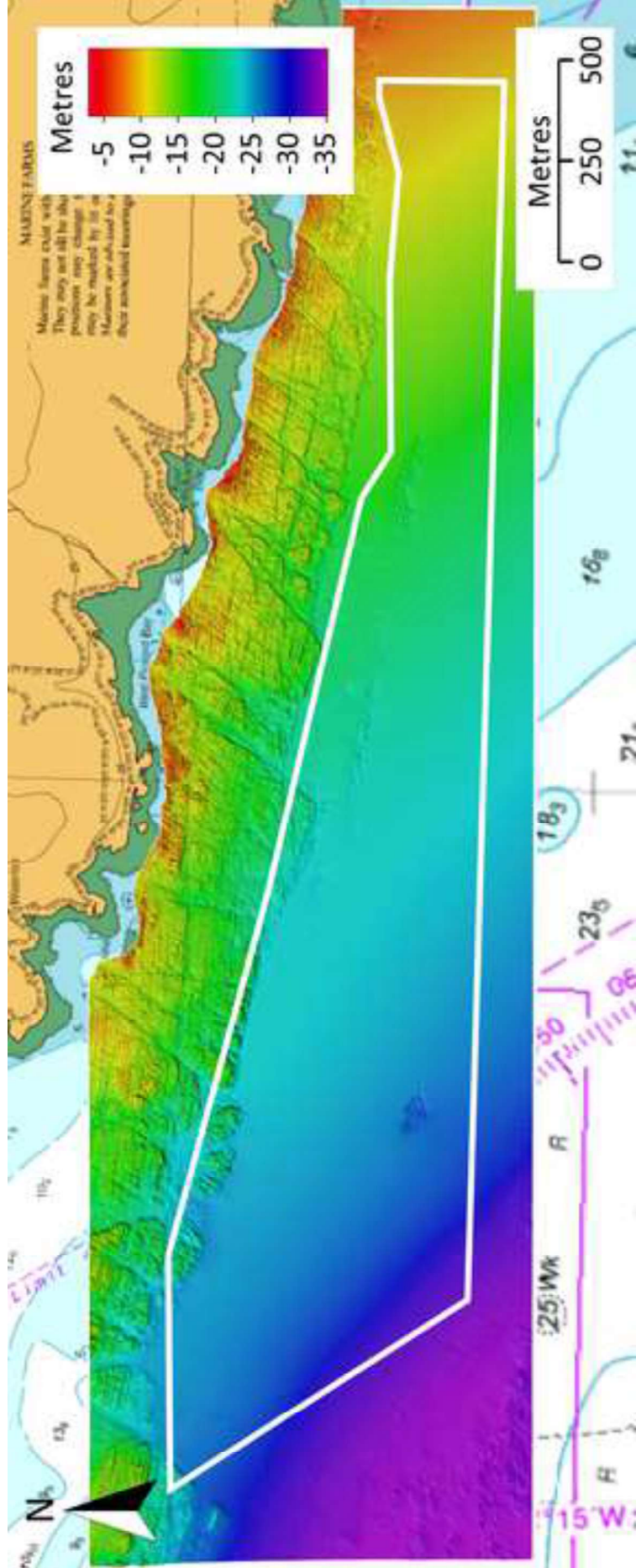


Fig 4

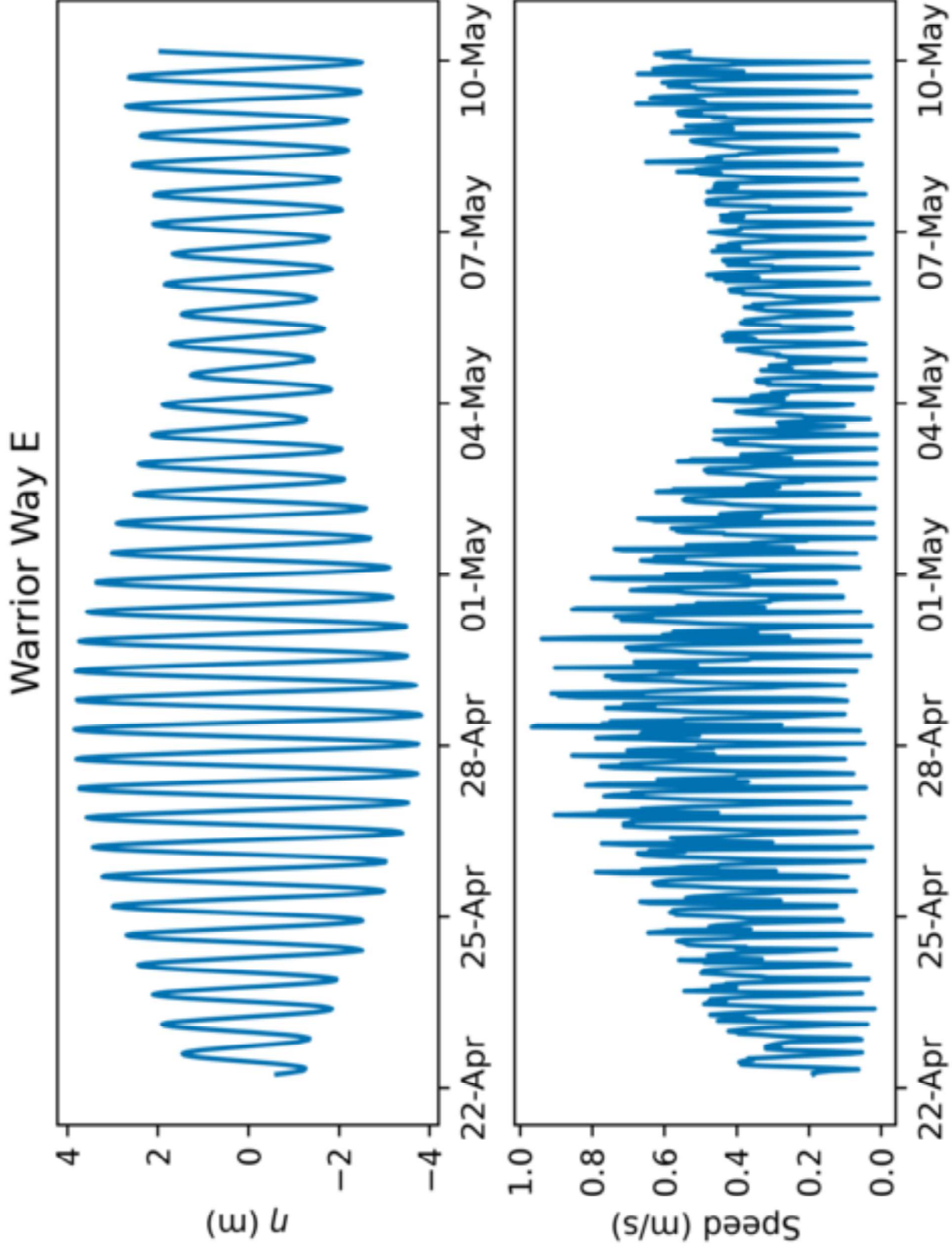
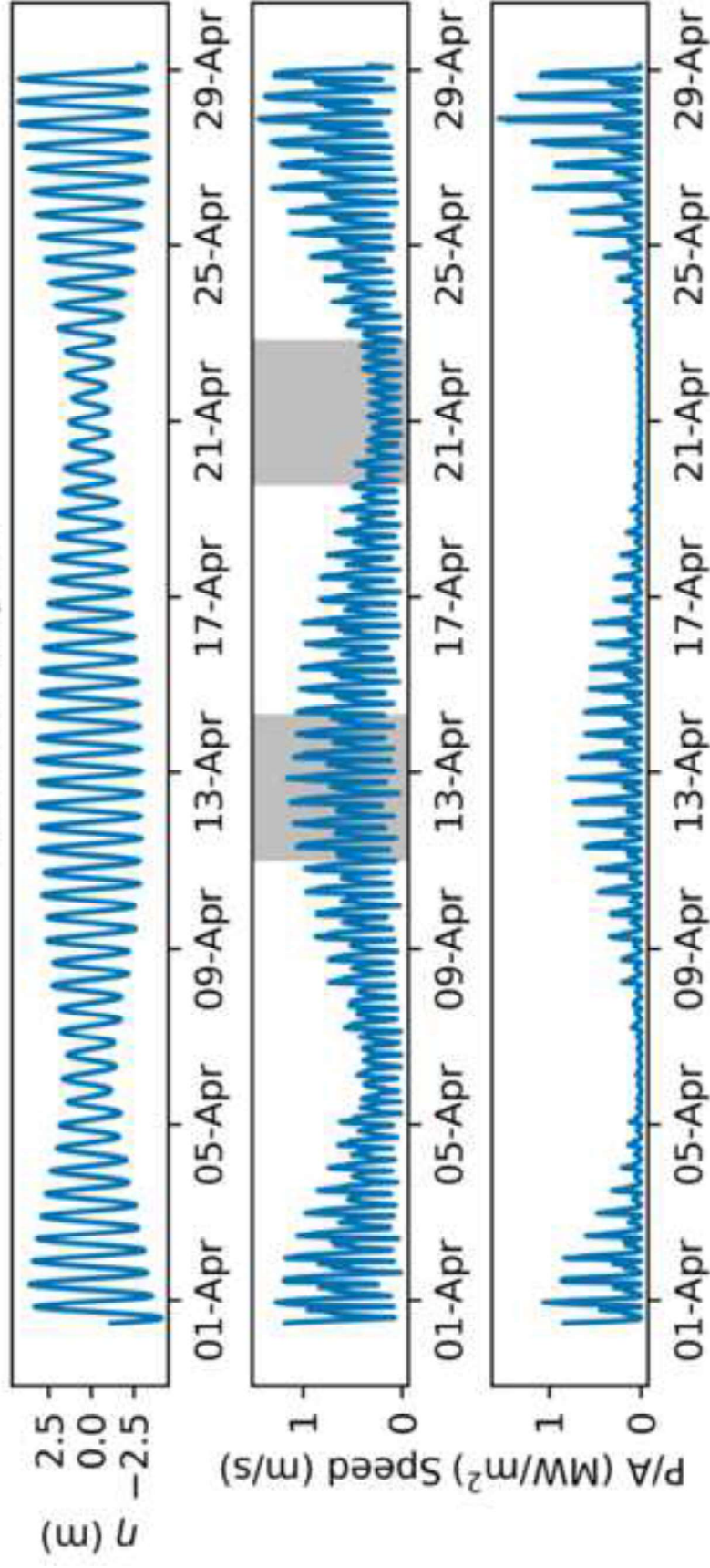
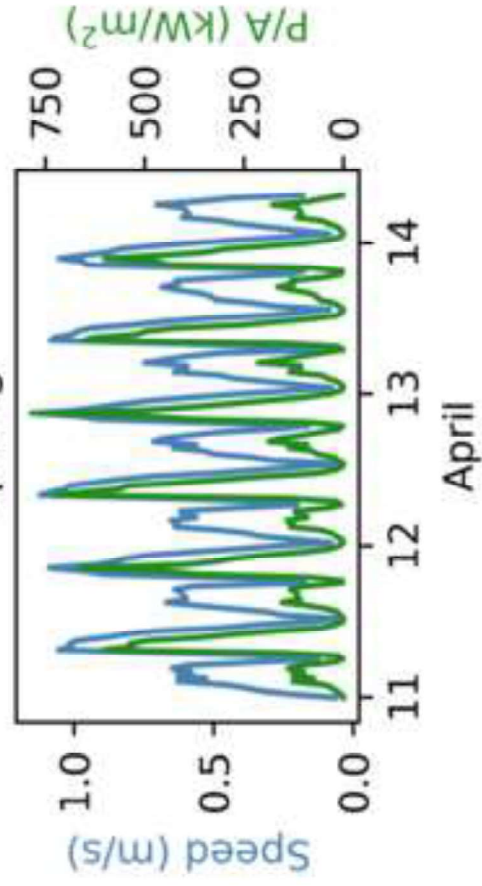


Fig 6

Warrior Way W



Spring



Neap

