Development of a Tool to Optimise Tidal Stream Energy Sites

Paul Evans, Jingjing Xue, Dan Williams, Matt Lewis, Matt Allmark, Allan Mason-Jones, Tim O'Doherty

Abstract—**Tidal energy developers seldom design devices to suit a particular site, rather devices are designed and suitable sites located subsequently. This reduces the number of viable sites as each device has its own design constraints, e.g. minimum water depth, minimum velocity, etc. In order to maximise the exploitability of these sites, where space is generally limited, it would be more beneficial for developers to design devices once site conditions/constraints are better understood.**

An open-source site selection tool is being developed that determines the physical constraints of a site based primarily on bathymetry and current velocities (measured and/or modelled). This tool aims to optimise a site to help developers understand what conditions need to be met in order to maximise energy generation – it will also identify which areas are unsuitable depending on the device design. The flexibility of the tool ensures two key aspects:

1. For existing devices, the device design parameters can be selected to show which areas are viable that meet these parameters (e.g. maximum bed slope, minimum current velocity, minimum water depth, etc.);

2. For devices yet to be designed, different design parameters can be selected to optimise a site to help maximise the energy that can be extracted from a particular site.

The current focus of the tool is on Ramsey Sound, Wales, UK given data availability and potential for a demonstration site to prove the tool's concept.

Keywords— **Tidal energy, site assessment, feasibility, resource, constraints.**

I. INTRODUCTION

Tidal stream energy in the UK is slowly becoming a reality, accelerated by the recent £10M ring-fenced support from UK government as part of the fifth round of contracts for difference auction (AR5). This, coupled with the current energy crisis, makes tidal energy more attractive than ever before. Shifting from pre-commercial demonstration projects to full-scale tidal arrays requires sites to be fully characterised in order to understand their often complicated nature. The UK has 50% of Europe's tidal energy resource [1] with an estimated 20.6 TWh/yr from 30 of the more appealing tidal stream sites [2]. However, these estimates tend to be based on relatively high-level, first-order appraisals with little consideration of the detailed and often complex site characteristics. It is only when sites are examined more closely that their viability is understood.

Attractive tidal stream energy sites are often located in areas that are subject to complex flow patterns, due in part to the bathymetry and coastline configuration. It is therefore vitally important to understand both the temporal and spatial variability of tidal currents.

II. RAMSEY SOUND

Ramsey Sound (Figure 1) is a strait located in West Wales, UK between Ramsey Island to the west and mainland Wales to the east. The strait is approximately 3 km long with a width ranging between 500 and 1600 m. Water depths are typically 20 – 40 m, but reach maximum depths of approximately 70 m within a north–south trending channel. A submerged ridge with a prominent pinnacle known as Horse Rock dominates the north-eastern quadrant of the strait. Roughly conical, this natural obstruction to flow has an estimated diameter of 100 m at its base and is approximately 23 m higher than the seabed around it. The crest pierces the water surface at low spring tides. Towards the south-western end of the Sound lies an emergent reef called The Bitches, which, coupled with Horse rock, create large areas of turbulence and complex flow patterns [3, 4, 5]. The area experiences a strong semi-diurnal tidal regime with a range of approximately 1.6 – 5 m from mean neap to mean spring.

In 2016, Tidal Energy Limited (TEL) deployed and tested a grid-connected full-scale prototype tidal stream energy convertor known as DeltaStream™. Unfortunately, this device developed a fault in its sonar system and could therefore no longer operate within its licence. However, a

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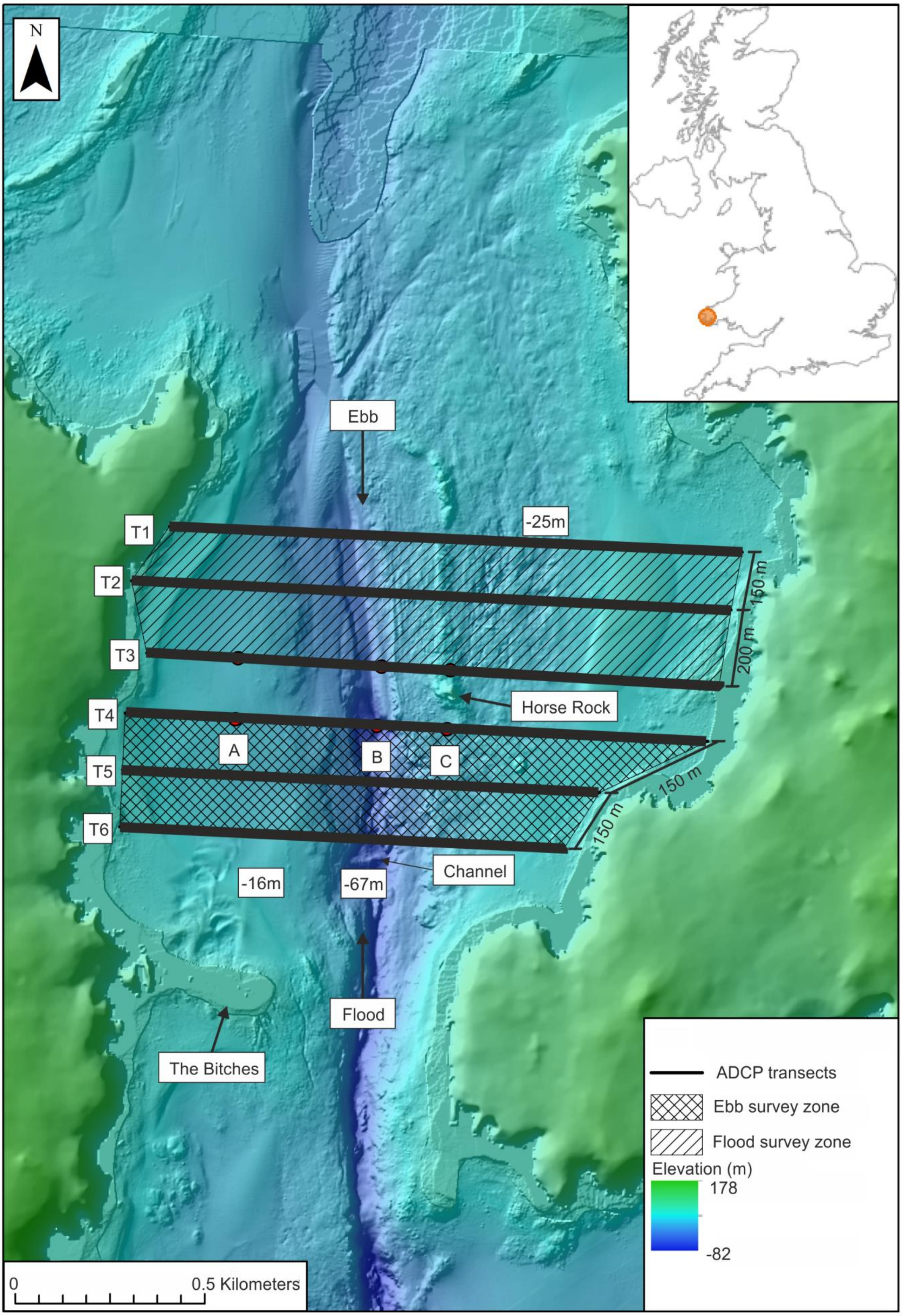

Fig 1. Ramsey Sound, West Wales, UK showing ADCP transects and bathymetry contours.

lot of lessons were learned while the device was in operation. This site is currently being considered by other tidal energy developers given the resource, however, given the site constraints (size, bathymetric features, complex flow patterns), this site is likely to only be a demonstration site going forward.

III. SITE CHARACTERISATION

To measure the tidal velocity data in the vicinity of Horse Rock, a four-beam 600 kHz broadband Teledyne RD Instruments Workhorse Sentinel ADCP unit was gunwhale-mounted on Cardiff University's Research Vessel, *Guiding Light*. The ADCP calculates current speed and direction through the water column by a combination of the Doppler shift and the timing of the returned echoes from suspended particulates. Trigonometric relations between the beams are subsequently used to calculate 3D current velocity vectors (u, v, w) that represent the longitudinal (north-south, x direction), lateral (east-west, y direction), and vertical (z direction) velocity components respectively.

The ADCP transducers were positioned 1.4 m below the water surface to ensure clearance from the vessel's hull with measurements being collected from 2.75 m below the water surface to near the seabed. The longitudinal (u) lateral, (v) and vertical (w) velocity components were recorded at a sampling rate of 1 Hz (one sample per second); the maximum sampling rate of the ADCP unit. Depth to the seabed was measured using the built-in bottom-tracking system, which was also used to calculate the vessel speed.

Surveying across the central portion of Ramsey Sound (Figure 1) was conducted over two consecutive days in June 2012, just prior to a peak spring tidal cycle. Flood-tide (flow travelling in a northerly direction) velocities were recorded in one day along a set of three transects (T1 – T3) to the north of Horse Rock; ebb-tide (flow travelling in a southerly direction) velocities were recorded the following day along a different set of three transects (T4 – T6) to the south of Horse Rock. Downstream distance from Horse Rock varied from 100 m (T3 and T4), 250 m (T2 and T5), and 400 m (T1 and T6). The transects cover a significant area of the Sound encompassing the deeper north-south trending channel as well as the shallower outer margins (see Figure 1). Each set of transects were surveyed in a continuous, five-hour circuit from one hour after slack water (Slack+1) to one hour before the next slack water (Slack+5). Although each three-transect circuit took approximately 30 minutes to complete, the simplifying assumption made here is that the data recorded during each circuit are representative of one twelfth of a given tidal cycle. Vessel transect time is a well-known limitation of vessel-based surveys relative to bottom-mounted instrumentation. However, the temporal and spatial resolution of the velocity measurements and transects employed herein are consistent with vessel-based methods used in previous studies of this type [4, 6].

Bathymetry within Ramsey Sound has been acquired from the United Kingdom Hydrographic Office (UKHO)

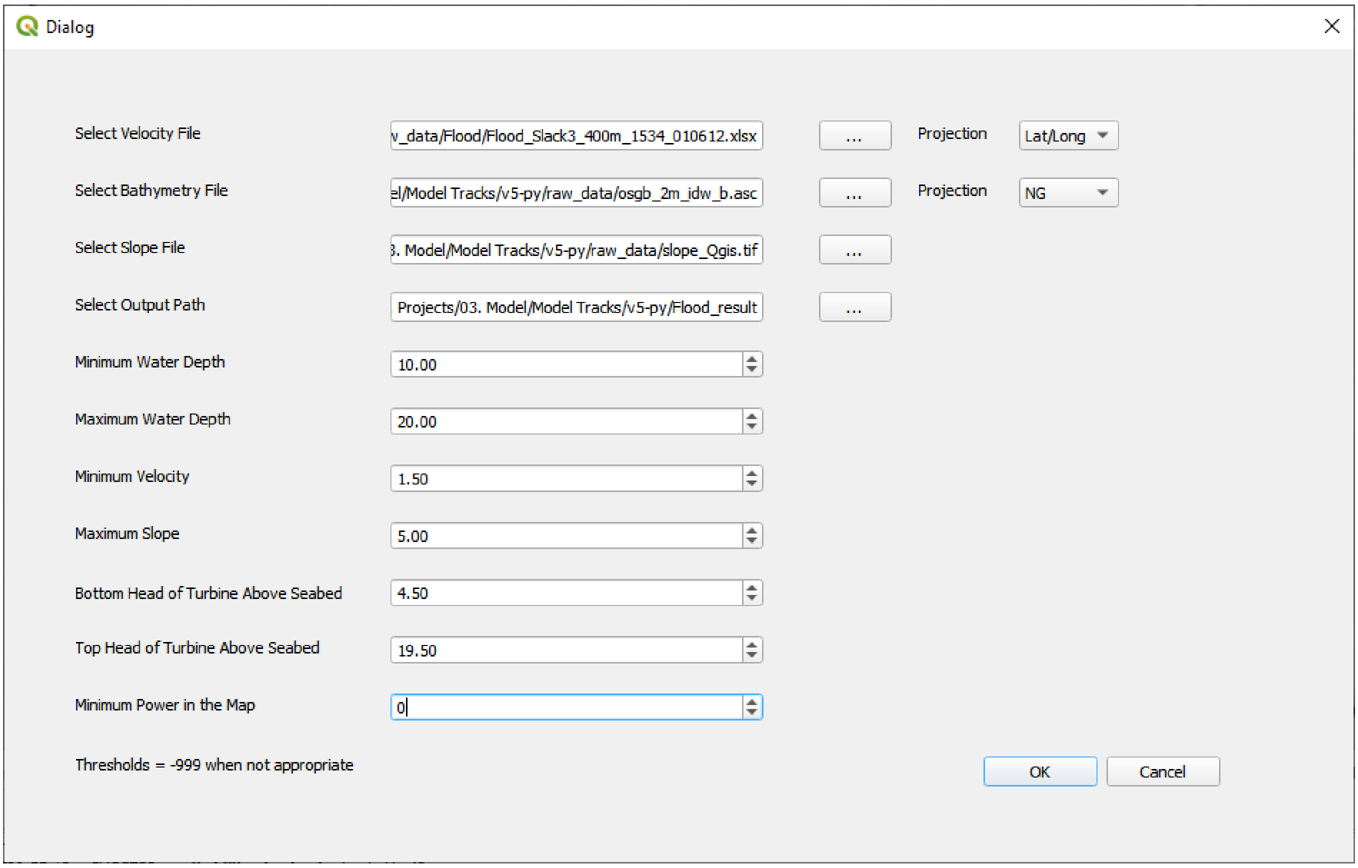

Fig 2. Suitability Tool dialog box.

TABLE I
TST SUITABILITY SCENARIOS

Scenario	Description	Minimum longitudinal, (u_v)̅, velocity (m s-1)	Minimum water depth (m)	Maximum bed slope (°)
Baseline	No threshold	-	-	-
1	Lower minimum velocity, lower water depth and no bed slope threshold	1.5	20	-
2	Lower water depth and no bed slope threshold	2	20	-
3	Lower minimum velocity and no bed slope threshold	1.5	30	-
4	Monopile design criteria (no bed slope threshold)	2	30	-
5	As Scenario '1' but with bed slope threshold	1.5	20	5
6	As Scenario '2' but with bed slope threshold	2	20	5
7	As Scenario '3' but with bed slope threshold	1.5	30	5
8	TEL's TST criteria	2	30	5

bathymetry data portal at a 2 m resolution. The 2 m bathymetry data was used to create a slope raster for input into tidal stream site selection tool.

IV. TOOL DEVELOPMENT

An open-source tool has been developed in Python with a QGIS plug-in. The dialog box is shown in Figure 2. The purpose of this tool at this stage is to assess a site's viability for tidal energy development based on an assessment of physical parameters, e.g. water depth, current speed and bed slope. The tool currently supports two key datasets: bathymetry and current velocities. As noted above, the bathymetry data is used to determine water depths and bed slope, while the velocity data is used to provide current speeds through the water column.

The tool has the flexibility of changing the various parameters based on a particular device design/constraint. For example, certain devices may only be able to operate economically at current speeds greater than 1.5 ms^{-1} and in water depths of 30 m or more. Similarly, another device may be able to operate at lower current speeds and shallower water. Bed slope may also be important for gravity based devices as opposed to devices that a piled into the seabed or floating. The tool also has the ability for users to assess current speeds at a particular elevation in the water column or average the data over a particular depth, e.g. the swept area of the turbine to focus on the current speeds for which the turbine itself will be subjected to. Should only depth-averaged velocities (e.g. a two-dimensional model output, for example) be available, this can be specified in the tool.

For the purposes of this paper, current speeds have been vertically averaged over 15 m to represent the diameter of the DeltaStream™ turbines. The vertically averaged data was subsequently linearly interpolated longitudinally along each transect and laterally over the three transects

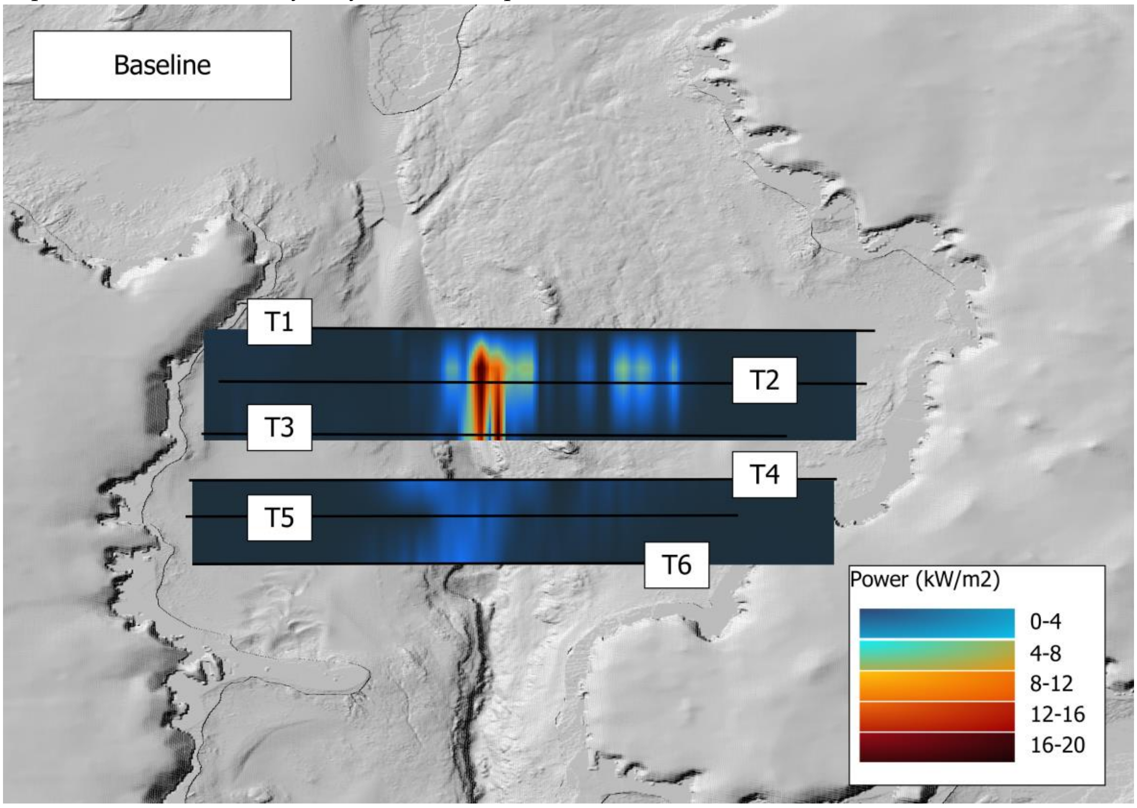

Fig 3. Baseline scenario

(T1, T2 and T3 during the flood tide and T4, T5 and T6 during the ebb tide) using an Inverse Distance Weighted (IDW) operator to create a raster of the horizontal current velocities.

The vertically-averaged velocities were then converted to power flux using the following:

$$P = \frac{1}{2}\rho A u^3 \quad (1)$$

where P is the power flux, ρ is water density (1,025 kg/m^2, A is the cross-sectional area of the turbine, and u is the velocity magnitude (sum of the longitude and latitude flow components. This equation shows that power is the cube of velocity and therefore small changes in velocity can lead to large changes in power output.

The next stage was to incorporate the 2 m bathymetry data and the slope raster for use in the suitability tool. The slope raster can be generated using the QGIS Plug-in tool, specifically the raster terrain analysis function, applied to the 2 m bathymetry data. This algorithm computes the terrain's inclination angle based on the bathymetry raster layer.

V. RESULTS

This tool allows the user to input either velocity, or bathymetry and slope, or both. Users also have the option to customise various design thresholds within the tool. These thresholds include minimum and maximum water depths, minimum velocity, and maximum bed slope. The user also has the option to specify the depth at which the velocities are averaged, for example over the turbine swept area, at a particular elevation within the water column or depth-averaged. Moreover, the tool allows for the export of the power distribution as a map independent of QGIS, with the option to set a minimum power threshold. In Figure 2, a default value of -999 is used to indicate no threshold for a specific parameter. Any area that fails to meet the defined thresholds will not be displayed in QGIS. To explore the impact of various turbine deployment design configurations, multiple scenarios outlined in Table I were modelled. Each scenario utilised a turbine with a swept area of 15 m, positioned with the nacelle centre 12 m above the seabed. Based on this setting, the top head of the turbine above the seabed turns to be 19.5 m, while the bottom head to be 4.5 m. Figure 3 presents the baseline scenario, that is the available power without any thresholds set, while Figure 4 shows suitable areas for each scenario. Scenarios 1-4 focus on examining the effects of the minimum velocity required for economic viability and the water depth parameters, without considering the bed slope. Scenarios 5-8 are with the maximum bed slope of 5° as listed in Table I.

Due to the flood-dominated tidal asymmetry observed in this particular area of the Sound, the available space that meets the defined thresholds during the ebb tide is relatively limited. Additionally, the suitability area diminishes as the minimum velocity requirement increases and the water depth decreases. Scenario 8 is based on the criteria of TEL's DeltaStream™ demonstration device, which could withstand a minimum water depth of 30 m and a maximum bed slope of 5°. A very small portion of the Sound meets these requirements during the peak of the flood tide. Furthermore, due to the lower velocities associated with the peak of the ebb tide, no viable areas are identified. It is important to note that the limited extent of suitable areas could pose challenges in practical implementation, especially when considering the design variations such as turbine arrays.

VI. DISCUSSION

This tool has demonstrated that device deign is an important consideration when assessing a site's viability, which has shown to be particularly sensitive to water depth and current speeds.

The application of this suitability tool has highlighted the importance of considering bed slope and device base width, factors that are often overlooked in the site selection process. Among all the tested scenarios, Scenario 1 stands out as offering the largest area for potential energy extraction. However, it is worth noting that this scenario, which assumes a minimum water depth of 20 m, presents clearance issues for vessels due to the use of a 15 m diameter turbine positioned 4.5 m above the seabed. To address this, exploring the feasibility of deploying smaller turbines would be a valuable avenue for future research. It is important to mention that this scenario does not account for bed slope, thus suggesting that only devices with a small footprint would be suitable in most areas. Additionally, a lower average velocity of 1.5 ms^{-1} has been utilized, which is unlikely to be sufficient given the current technological limitations and the economic considerations associated with harnessing tidal streams for power generation.

The presence of power hotspots in the region with high velocities around Horse Rock is evident; however, the steep bed slope poses a new challenge for the placement of TSTs, particularly for gravity-based systems [4]. Coastal areas are seldom flat and often exhibit significant irregularities, which change the local flow patterns. Irregular or undulating seabeds are generally better suited for piled foundations due to the difficulties involved in preparing the bed for gravity structures [7]. Several tidal-stream turbines are gravity-mounted and can only tolerate relatively low bed slopes. For example, TEL's DeltaStream™ device could only withstand a maximum bed slope of 5° [3], resulting in a base width of 20 m with a vertical drop of 2 m across the structure, while a 5 m base width corresponds to a 0.5 m drop. Lower bed slopes are desirable to maintain stability at the base. The maximum tolerable bed slope depends on the device's mounting and anchoring arrangement but could be increased for a piled device. In this study, a gravity-based device or a small

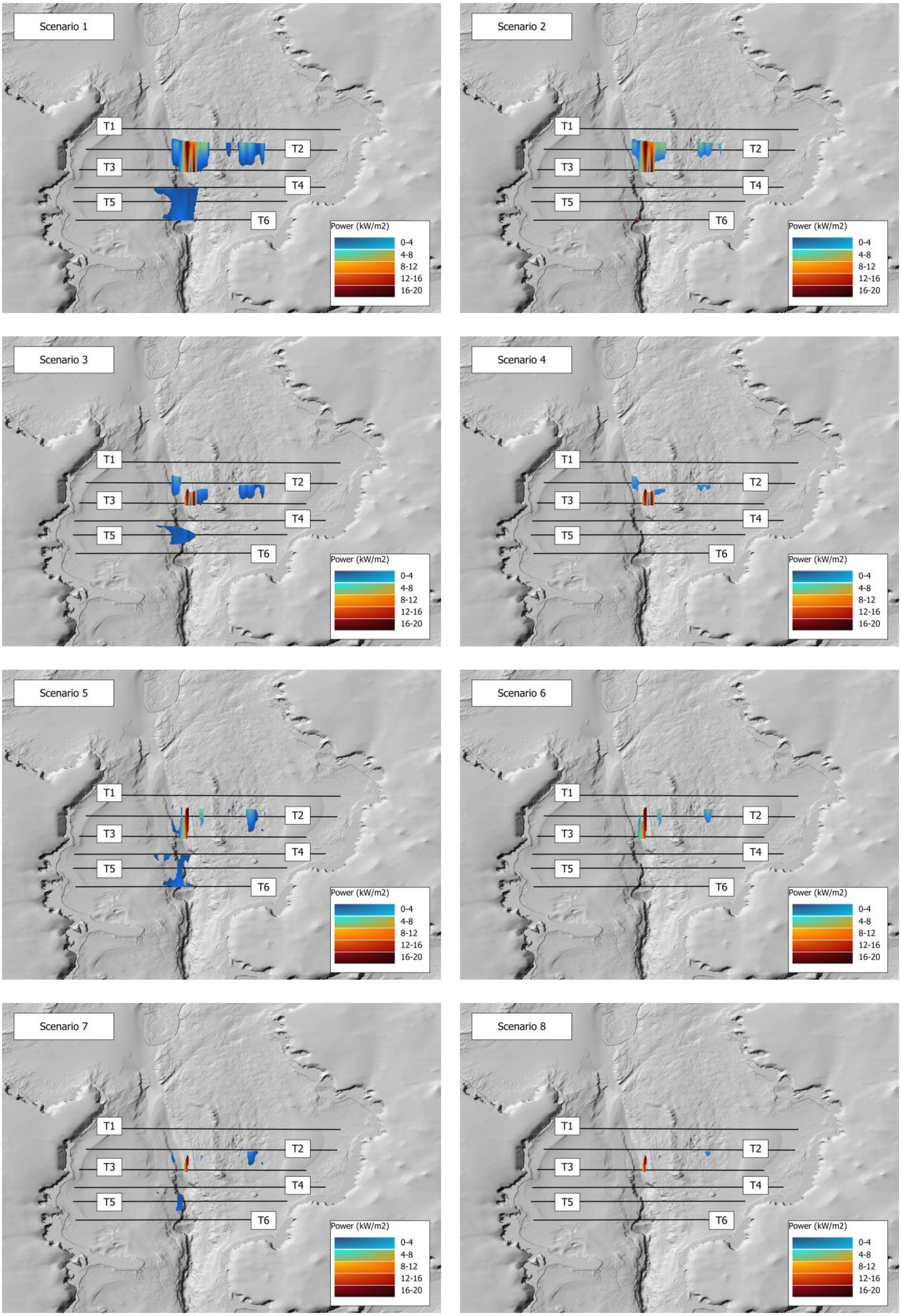

Fig 4. Suitability Tool output.

array of turbines sharing a common structure was assumed. However, due to the local bed slope in several locations within the Ramsey Sound channel, the high-energy zones become functionally inaccessible without any blasting or excavation of the channel bottom.

Water depth represents another limiting factor for turbines. These devices typically extend approximately 20 m from the seabed to the tip of the turbine. It is generally recommended to maintain a minimum clearance of 5 m to accommodate recreational activities (such as small boats and swimmers), minimise turbulence and wave loading effects on the TSTs, and prevent damage from floating debris. This recommendation assumes the creation of an exclusion zone that restricts vessels with a draught greater than 2 m [8]. Consequently, a minimum water depth of 25 -30 m, including a 5-10 m freeboard, is typically required. The bathymetry data in Figure 1 reveals large areas that meet this criterion, but they are mostly confined to the deep channel.

It should also be noted that vessel activity within Ramsey Sound is primarily limited to local fishing and coastal vessels, which rarely have a draught extending more than 5 m below the water surface. If shipping is restricted in the vicinity of the TST, the aforementioned rules can be relaxed.

VII. CONCLUSION

This paper has detailed the development of an open-source site selection tool for tidal stream energy devices. Three principal physical parameters have been tested (water depth, bed slope and current velocity) using Ramsey Sound, Wales, UK as a case study. It has been shown that site suitability is highly sensitive to these parameters, and when other constraints are considered, e.g. nature designations, protected areas, maximum distance offshore, etc are factored in, areas are suitability are likely to diminish.

The tool is currently in proof of concept phase using the aforementioned data collected in Ramsey Sound as a case study. The intention is to expand this tool to handle different datasets (e.g. modelled outputs) and assess different locations, both in the UK and overseas, including the wider Ramsey Sound region, as well as incorporate other constraints, as detailed above.

The results of the study recommend to design tidal streams turbine devices based on identified hydrodynamics and physical constraints, rather than designing a device and then searching for suitable locations that meet its specific requirements. This approach ensures a broader range of sites can be considered and prevents the exclusion of potential locations based on individual physical parameters. While this approach may incur higher initial costs, it enables the installation of a greater number of tidal streams turbines, leading to increased energy production and a higher economic return in the long run.

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