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Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Kelly, CL, Blanco-Davis, E, Michailides, C, Davies, PA and Wang, J (2018) Site Selection Appraisal for Tidal Turbine Development in the River Mersey. Journal of Marine Science and Application, 17 (1). pp. 112-121. ISSN 1671-9433

Site selection appraisal for tidal turbine development in the River Mersey

C.L. Kelly[a], E. Blanco-Davis, C. Michailides, P. Davies, J. Wang

Department of Maritime and Mechanical Engineering, LOOM Research Centre, Liverpool John Moores University
Liverpool, L3 3AF, UK

Abstract

This report used a specialist software package to produce a detailed model of the River Mersey estuary, which can be subjected to a range of simulated tidal conditions. The aim of this research was to use the validated model to identify the optimal location for the positioning of a tidal turbine. Progress was made identifying a new optimal site for power generation using velocity data produced from simulations conducted using the MIKE 3 software. This process resulted in the identification of Site 8, which sits mid-river between the Morpeth Dock and the Albert Dock, being identified as the favoured location for tidal power generation in the River Mersey. Further analysis of the site found that a 17.2m diameter single rota multidirectional turbine with a 428kW rated capacity could produce 1.12GWh annually.

Keywords; Tidal power, River Mersey, MIKE 3

Abbreviations

M1	MIKE Zero: Modelling and mesh generation
M2	MIKE Toolbox: Global tidal model data
M3	MIKE 21: Simulation software for flow modelling of costal marine areas
MSL	Mean Sea Level
TEC	Tidal energy convertor
X	Horizontal displacement
Y	Vertical displacement
Z	Depth displacement

1. Introduction

Twice a day the River Mersey undergoes the second largest tidal shift in the UK. As a result, a large volume of water flows in and out of the River Mersey estuary providing a vast untapped source of tidal energy that could be extracted using a range of tidal energy technologies.

Previous studies have been conducted by the Mersey Barrage Company between 1988-1992, and the Mersey Tidal Barrage Group between 2006-2011. Both these studies examined the uses of a tidal barrages to control the flow in order to power tidal turbines, in order to produce a reliable and predictable source of energy. Both reports concluded that the optimal location for a tidal barrage would be between New Ferry and Dingle, and could potentially produce up to 920GWh of energy per year. However, the estimated construction costs alone had a staggering £3.5 billion price tag and, as a result of low energy prices, the project has been unable to secure funding from investors (Peel Energy, 2011).

There are a number of alternative methods of extracting tidal energy that have been under development and testing. They include the SeaGen turbine in Strangford Lough, which is in operation since 2007 and became the first tidal stream generator to be connected to the National Grid in 2008 (supplying 1.2MW for 18 to 20 hours each day-equivalent to an annual supply of 6GWh). This was a key milestone for tidal stream generators and proved their viability as a reliable source of power generation (Marine Current Turbines Ltd, 2008).

When examining the geographical terrain of Strangford Lough it became apparent that it shared a number of key geographical characteristics with the River Mersey, such as a narrow bottle neck leading to a large inlet and a large tidal range. An initial investigation into the potential for the positioning of tidal turbines in the River Mersey has been carried out previously (Kelly, 2015). This resulted in a very simplistic analysis for a small section at the river mouth between Perch Rock and Gladstone Lock, which concluded that there was the potential to produce 13.6 MWh per lunar month from a single rotor multidirectional turbine located at Site F situated in the middle of the river mouth. The output for this site was severely constricted due to the shallow depth and the relatively slow flow at the identified site in the river.

This research has set out to validate the initial feasibility study, by conducting a holistic assessment of the Mersey estuary in order to identify additional sites that might be better suited to tidal power generation. In order to achieve this, the initial aim of producing a computer model of the river basin from the original report was revisited using the specialist tidal flow simulation software package, MIKE 3, which has been developed by DHI Group and is currently used in the coastal and fluid engineering sector.

[a] Corresponding author (C.Kelly1@2012.ljmu.ac.uk)

2. Development of the numerical analysis model for tidal power assessment

The software developed by DHI has been widely used in industry as a simulation tool for a variety of different hydrodynamic conditions. The software is extensive and broken down in to a number of sub programs in order to streamline the simulation process depending on the type being conducted. In order to conduct a tidal flow simulation, the following main sub programs were to be used:

MIKE Zero:	Modelling and mesh generation
MIKE Toolbox:	Global tidal model data
MIKE 21:	Simulation software for flow modelling of costal marine areas

Below is a description of the sub programs that are used for the development of the numerical models are presented.

3. Mike Zero:

In order to generate a realistic model, accurate data for three boundaries conditions have to input to identify shoreline, river depths and river inlet location. The shoreline and river depth data have to be imported into the model in the format of text files, in order to provide the required data for the software tool to produce the boundary conditions for the model. The inlet boundary could then be specified using a tool in the software. This tool identifies the section that will drive the simulation process using data obtained from the global tidal model.

3.1. Shoreline boundary condition

The shoreline data is required by the model to provide a boundary restricting the flow of the river in the X and Y directions. To obtain the data for the River Mersey shown in Fig. 1, the Admiralty Chart 3,490 and the Ordnance Survey Map Sheet 108 were used to find the longitude and latitude values, for points along the banks of the river starting at Perch Rock working the way around the Basin to Gladstone Lock. The software could then be used to generate a solid boundary between these points by assigning each value a connectivity of one. This identified to the software that each point was connected to the next. In order to simulate the exit to the sea at the river mouth, the last data point at Gladstone Lock was assigned a connectivity value of zero indicating opening between Gladstone Lock and Perch Rock to the software.

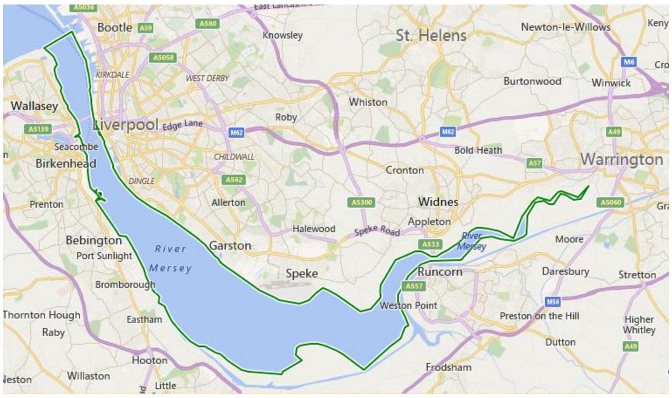

Fig. 1. River Mersey (Google Maps, 2017)

On a spring tide the effects that the tide has on the River Mersey can be observed as far up stream as Howley Weir in Warrington. However, for the purpose of reducing the complexity of the model, the river basin was effectively cut off at Runcorn Bridge. This was chosen due to the constriction in the river at this point and the absence of depth data for the area upstream.

3.2. River depth boundary condition

The river depth data file was used by MIKE Zero software to create a boundary condition in the Z direction. Using the Admiralty Chart the longitude and latitude for known depth values could be recorded and the data added to the model.

Regrettably the Admiralty Chart only provided river depth data for the area between Perch Rock and the entrance of the Manchester Ship Canal (the main shipping route). Additional data could not be sourced for this area due to the constantly shifting river bed conditions that occur due to sediment transportation. In order to provide enough data for the model, estimates for the depths in this area had to be made using estimations based of known data from the chart. They were used in conjunction with known data from the chart in an attempt to provide a realistic prediction for river depths in this area.

In order for the depth data obtained to be used in the model it had to be adjusted from chart datum to mean sea level (MSL). This involved adding 4.93m, the MSL specified by the chart, to each of the depth values which had been recorded from the lowest astronomical tide.

3.3. Inlet boundary condition

In order to specify an inlet in the model, the last shore line data points at Perch Rock and Gladstone Lock had to be selected using the inlet tool in the MIKE software. This tool could then be used to specify the area between as the inlet boundary.

For the purpose of this study the flow of water was simulated using only the change in tidal height data. As a result, the volume of water due to the natural flow of the river itself was not considered. This assumption can be considered as valid, since the flow of the river contributes just 1% of the flow exiting the estuary, and therefore only accounts for a relatively small amount when compared to the volume that flows in and out due to the tidal shift. (The National Oceanography Centre , 2016).

3.4. Conversion of longitude and latitude values

After initial modelling attempts failed to situate the model in the precise location within the global model, it became clear that the model was not able to handle the format in which the longitude and latitude data had been recorded. In order to rectify this problem, the longitude and latitude data for both the shore line and river depth boundary conditions had to be converted from the standard format of Degrees, Minutes and Seconds into Decimal Degrees using Equation (1) (Rapid Tables, 2016).

$$Decimal\ Degrees = Degrees + \frac{Minutes}{60} + \frac{Seconds}{3600} \tag{1}$$

3.5. Meshing process

Once the boundary conditions had been incorporated into the MIKE Zero software, an initial mesh is produced and then refined if needed. By refining the mesh, the number of nodes was increased adding further detail to the model. The Redistribute Vertices tool was used to increase the number of nodes that provided the boundary conditions for the river bank, by using a predictive modelling tool to insert extra data points every 200m along the banks. This resulted in a slight change to the profile of the river since the software is used to deal with curves and meanders of most typical shorelines, and not the straight edges of the river Mersey. As a result of this refinement process there will be a slight error in any data recorded close to the banks however, this was considered appropriate because turbines would not be positioned in these areas. Further refinement was carried out in order to adjust the conventional mesh between data points and produce a refined mesh for the riverbed in the main channel.

The mesh refinement process was limited due to the 1,000 node limit imposed by the student licence of the MIKE 3 software. Considering that the initial data accounted for 472 nodes, there was very little room for refining the mesh, however the final mesh consisted of 964 nodes. The final mesh can be seen in Fig. 2 which also shows the boundary condition for the inlet (green line), shoreline (red dots), and depth points overlaid on the grid of longitude and latitude values.

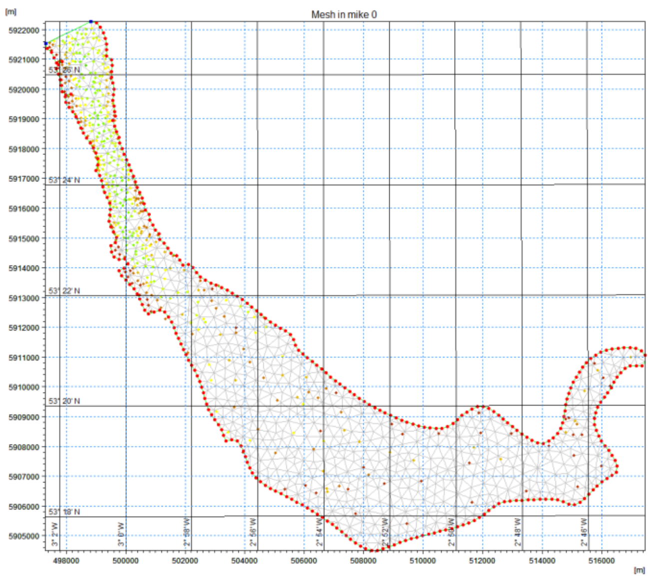

Fig.2. Final model mesh

4. MIKE Toolbox

Once the inlet boundary conditions had been specified using MIKE Zero, the MIKE Toolbox application is then used for finding the tidal flow expected at the precise location using data from the built-in global tidal model. In order to validate the output data, tidal data for the period between 21/02/2015 and 23/03/2015 that corresponds to the period of one lunar month, is used as input to the corresponding analysis.

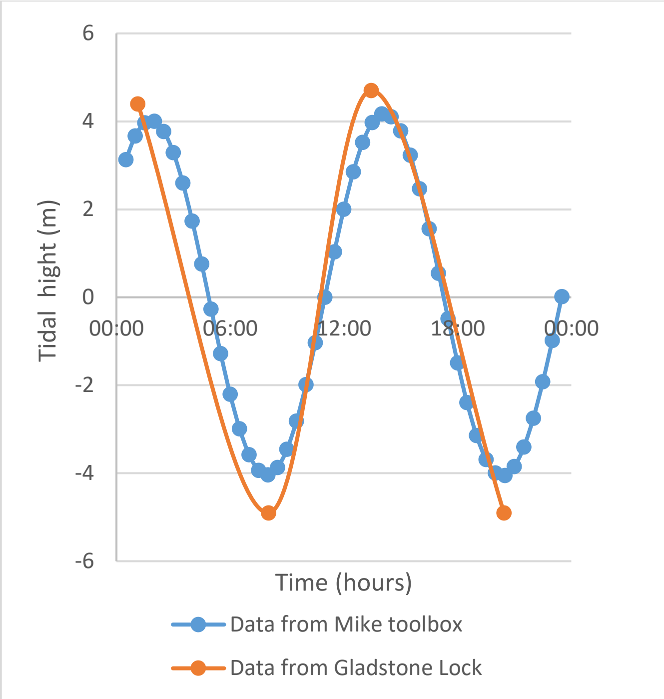

Fig.3. Comparison of tidal data for 22nd February 2015

In order to validate the data taken from the global model, a comparison was drawn against the tidal data that was predicted to occur at Gladstone Lock over the same period examined. An example of this comparison can be seen in Fig. 3 which shows the predicated and recorded data for the 22nd of February 2015. The graph indicates a strong correlation between the model and the recorded data, however a slight discrepancy of around 0.4m was observed between the high and low tide values.

5. MIKE 21

Using the mesh file created in MIKE Zero and the data obtained from MIKE Toolbox, an initial simulation could be run using MIKE 21.

5.1. Initial simulation

Initially a simple area analysis simulation was conducted to visualise the flow thought the model. This analysis also provided preliminary water depth, velocity, and direction of the flow data; the last could then be used to confirm that the simulated flow through the model was as in line with expectations. In order to achieve this, a simulation for the 30-day period was carried out using a time period of one iteration per minute, resulting in a simulation period of 43,200 iterations. This produced a minute-by-minute analysis of the changing flow rates and river depths, which was displayed using a polychromatic contour plot overlaid on the model. Some of the results of which can be seen in Fig. 4.

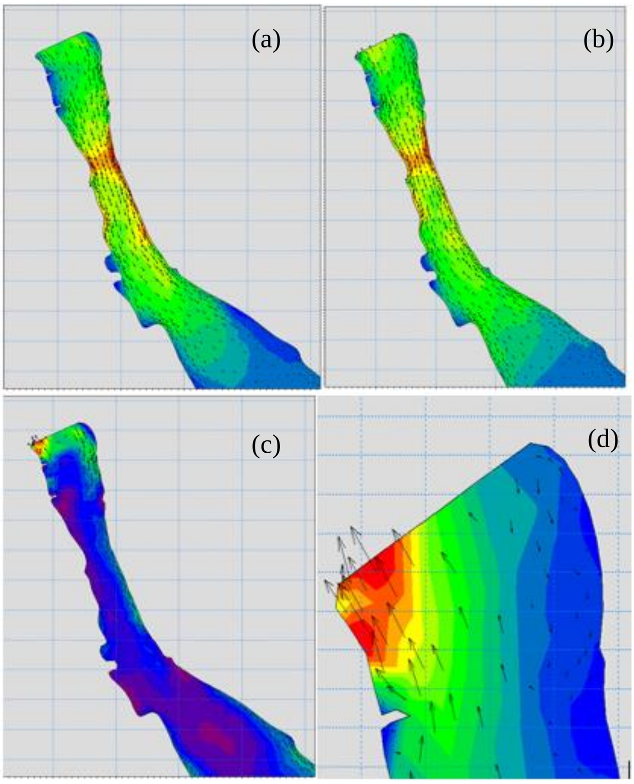

Fig. 4. Pictures showing (a) flow in; (b) flow out; (c) change of the tide; (d) recirculation at low velocities near the entrance

This initial simulation confirmed that the model worked as expected and simulated different flow conditions in and out of the river, as the tidal height at the inlet varied over the time period. However, two initial problems were identified:

a) Discrepancies between the simulated flow velocities and the data provided by the Admiralty Chart

b) Recirculating flow at the inlet boundary during periods of low velocity.

5.2. Validating the model

Due to the concerns brought about by the initial area series analysis, further tests were carried out in order to validate the model. This was done by comparing data produced during the simulation to known velocity data provided at each of the tidal diamonds on the Admiralty Chart. The tidal diamonds on the chart indicate flow speeds at hour intervals for six hours before and after a spring and neap tide. In order to make this comparison, data had to be gathered from the model using a point series analysis, allowing data to be gathered from the model at the precise location of each of the tidal diamonds.

Despite attempts to fix the turbulent flow at the model inlet, no further improvements could be made. As a result, any data generated by the model for the section between the inlet and Tower Groyne was considered corrupt. This meant that data generated for this section of the river was discarded, resulting in the failure to complete the initial aim of validating the original report.

In order to validate the remaining area, a simulation was conducted for a six-hour period before and after high tide for a spring tide on the 21st February and a neap tide on the 27th February 2015, in order to find the velocity at the specified tidal diamond points B, C and D. The data could then be compared to the Admiralty Chart data for the tidal diamonds B, C and D. Point A was discarded from the process due to its location in the area affected by recirculating flow, which corrupted the data. See table 1 for precise locations of each tidal diamond.

Table 1. Location of tidal diamonds A to D

	Longitude	latitude
A	53°26'82 N	3 01·78 W
B	53°25'52 N	3 00·98 W
C	53°23'02 N	2 59·78 W
D	53°22'12 N	2 58·48 W

It was immediately apparent that the data for the initial model was drastically different from the expected values. Further examination and simulations revealed that this was due to a restriction in the volume of water that could flow into the estuary, which was not sufficient to produce the expected flow velocities. This was caused by the conservative estimates that had been made for the unknown depth values which, as a result, restricted the volume of water that could be contained in the estuary.

In order to adjust the amount of water flowing into the estuary, the estimated depth values in the initial model were altered to increase the volume of water flowing into the model, and the comparison process repeated. This procedure was repeated a number of times until a close correlation between the simulated and expected values was achieved.

Fig. 5 shows the comparison between the simulated and known values for the final model, which clearly suggests that the model corroborated the data to a respectable degree of accuracy validating the altered depths of the model.

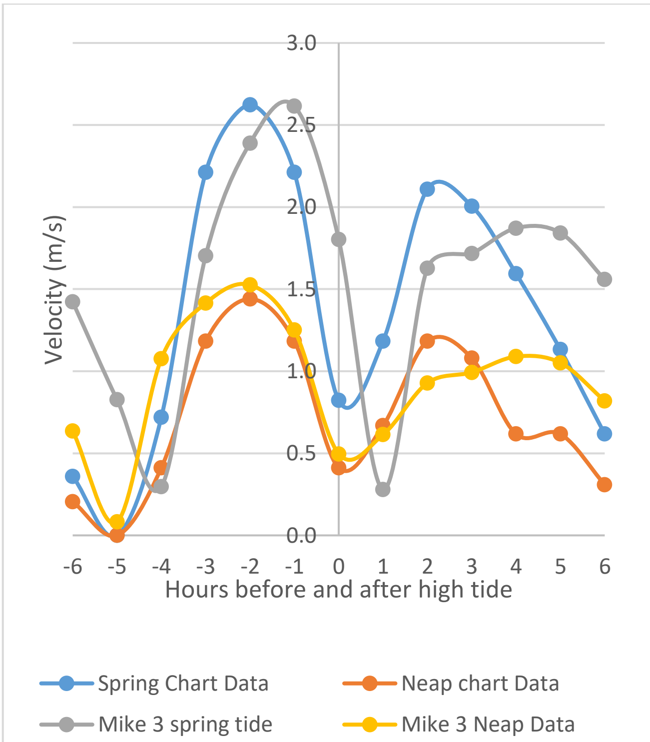

Fig. 5. Comparison of flow velocity at tidal diamond C for

flow data generated during the simulation and data obtained from the Admiralty Chart for the spring and neap tidal flows

5.3. Optimal locations

The power that can be extracted for the case of a tidal stream generator is given by Equation 2. Due to the assumptions that the density of sea water remains at a constant 1,025kg/m^3, and that the efficiency of the turbines at each potential site would remain same, only two parameters in the equation can be varied to affect the power produced by the turbine: the swept turbine area and the velocity of the flow. Both of these are constricted by the profile of the river.

$$P = \frac{\rho A V^3}{2}\eta \quad (2)$$

Where, ρ is the density of sea water (kg/m^3), A is the swept area of the turbine blades (m^2), V is the velocity of water flowing through the turbines (m/s), η is the mechanical efficiency of the turbine. P is the power generated (W),

As a result of this, a second area series analysis is conducted. This allowed for the identification of areas of interest through the examination of the velocity and the depth data generated from this simulation, so that potential turbine locations could be identified.

In order to pinpoint the location for a turbine in the river the data produced by the analysis was examined using these two key criteria points to identify potential turbine sites. This was done to determine if a deeper location, which could accommodate a larger swept area, would be better than a faster flowing section of the river, which normally has shallower depths that restrict the size of the turbines swept area.

Fig. 6 (a) shows the location of turbine sites 1 to 5 in the area identified as being the fastest flowing section of the river which, as expected was the narrowest section of the river.

The second Fig. 6 (b) indicates the location of turbine sites 6 to 10, which were selected based on a depth analysis that identified some of the deepest locations in the river.

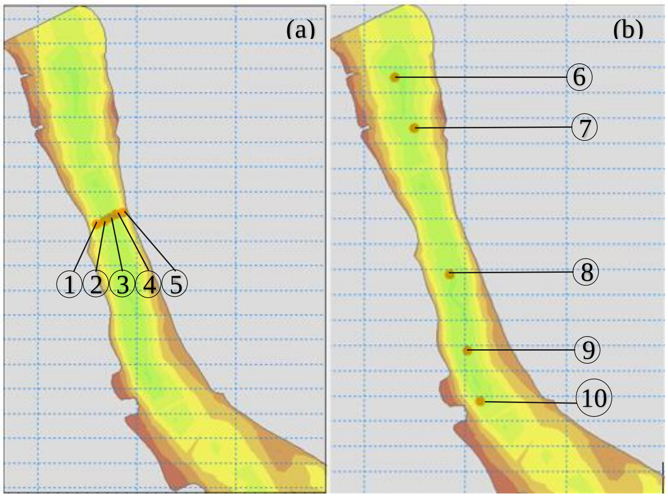

Fig. 6. (a) Location of turbines sites 1 to 5 from left to right, in the fastest flowing section of the river (b) Location of turbines sites 6 to 10 from top to bottom in deep areas

A point series analysis was then conducted in order to gather precise information, at each of the identified turbine locations for an entire simulated lunar cycle. This allowed for data to be gathered over a range of different tidal conditions. In turn, this allowed the power outputs for each site to be calculated by using the average velocity obtained during this period. In order to find the potential power at each point, a 100% efficient multidirectional turbine was simulated.

In order to calculate the swept area of each turbine, the minimum depth at which water speeds were in excess of 1m/s was identified from the data. In order to account for the clearance between the turbine blades and the seabed, the depth value was modified by -1.5m before the swept area was calculated.

Table 2 shows the results of the initial average power outputs that can be expected from the ten potential sites identified. The comparison identifies Site 8 as the most efficient location for the positioning of a turbine with the potential to produce an average of 219kW over a lunar period. Site 3 was also identified as another potential location producing 204kW during the same period. Since each turbine site had initially been selected using the different identification criteria, it was decided that both sites should be examined in greater detail in order to determine the optimal location in case the initial location criteria affected the potential outputs of the turbine.

Table 2. Average power produced at each turbine location

Turbine site	Swept area (m^2)	Average velocity (m/s)	Power (kW)
1	74	1.54	137
2	105	1.53	193
3	110	1.53	204
4	104	1.54	194
5	54	1.67	128
6	191	0.93	79
7	192	1.18	163
8	232	1.23	219
9	211	1.19	183
10	140	1.15	109

6. Power

In order to compare Sites 3 and 8 in greater detail, the velocity data for the entire lunar period was examined to account for actual conditions at each location. To provide a realistic power output that could be expected at each site a number of assumptions had to be made. Due to the availability of data that exists on tidal turbines, some of the assumptions were based on the data recorded at the SeaGen turbine in Strangford Lough.

6.1. Assumptions

The following assumptions were made for the given reasons:

- Multidirectional turbines were simulated to account for power generation from the flow in any direction.
- The simulation will analyse the uses of a single rotor turbine positioned at each site.
- Rated power for the turbine in each location was limited to the power produced by a flow of 2m/s thought the swept area.
- Turbines required water speeds in excess of 1m/s in

order for the turbine to become operational.
- Efficiency of the turbine was taken as 45% to account for losses. This value is the lowest operating efficiency that has been observed at the SeaGen site since it became fully operation in 2008. (Martin Wright, 2010)

6.2. Rated power

The rated power of a turbine is the maximum power output that can be achieved by a turbine. In order to calculate the rated power of the turbines at each site, a simple power calculation was conducted to find the power produced when the velocity of the water was 2m/s. Due to the variation in turbine diameters there was a difference in the rated power calculated for each site. The turbine located at Site 3 was an 11.9m diameter turbine rated to 208kW whereas Site 8 encompassed a 17.2m diameter turbine rated at 430kW.

6.3. Power produced

In order to calculate the power produced at each location the velocity data for the two sites was examined and organised into three flow phases specified as:

- Non-operational velocity less than 1m/s
- Cut-in velocity between 1 to 2m/s
- Rated power velocity over 2m/s

Since data had been gathered in one-minute increments, it could be used to calculate the percentage of time that the turbine was operating for each of specified phases during the lunar period. The results of which can be seen in Table 3.

Table 3. The percentage of time spent operating in each period over the lunar month

Group	Site 3 (%)	Site 8 (%)
Rated power	11	7
Cut-in	67.4	62.5
Non operational	21.6	30.5

In order to calculate the average power generated at any given time by the turbine, the power calculated for each of the specified phases was found using the velocity values. To find the power produced during the rated power period a velocity value of 2m/s was used, due to the initial assumption made limiting the power of the turbines. The non-operational period was calculated using a velocity of 0m/s. This was due to the assumption that flow rates of less than 1m/s were not strong enough to power the turbine resulting in a zero power output during this period. In order to calculate the power produced during the cut-in phase, the velocity was calculated using the average of all the data between 1 m/sec and 2m/sec.

By multiplying the power values calculated for each phase by the percentage of time, the average power produced during that phase could be calculated as seen in Table 4 for the turbine at Site 3 and Table 5 for Site 8.

Table 4. Power outputs for different periods at Site 3

	Time (%)	Velocity (m/s)	Power (kW)	Average power over time period (kW)
Rated power	11	2	208.6	22.9
Cut-in	67.4	1.67	122.2	82.3
Non-operational	21.6	0	0	0

Table 5. Power outputs for different periods at Site 8

	Time (%)	Velocity (m/s)	Power (kW)	Average power over time period (kW)
Rated power	7	2	428.7	29.9
Cut-in	62.5	1.42	156.4	97.8
Non-operational	30.5	0	0	0

The average power for each phase could then be combined to find the average power produced over the lunar period, resulting in an output of 105.2 kW at Site 3 and 127.7 kW at Site 8. This confirmed the initial calculations identifying Site 8 as the most efficient location in terms of produced power for a tidal turbine between ten different locations.

7. Discussion

7.1. Site 8

Site 8 is situated mid-river between Morpeth Dock and Albert Dock. A single 17.2m rotor multidirectional turbine located there would be able to produce an average output of 127.7kW over the lunar period, however on average the turbine will be non-operational for 30.5% of the time due to the low velocities of the flow at this point. This means that the turbine would be operational for an average of 17 hours a day. During which the maximum capacity of 430kW would be achieved for a period of one and a half hours. The average power produced during the operational phase is 183kW. In total the turbine would have the potential to produce 91MWh per lunar month, which equates to an annual output of 1.12GWh.

However, due to the site location in one of the busiest sections of the river, a turbine is unlikely to be deployed at this location due to the increased hazard that it would pose to any vessels that are navigating to one of the many surrounding areas, including the Liverpool Cruise and Tranmere Oil Terminals and the docks at Cammell Laird Shipyard and Brunswick.

7.2. Comparison to initial feasibility results

Even though the results of the initial feasibility study could not be verified, a comparison could still be made between the annual power outputs calculated for the sites identified in each report. The first report found that an 11m turbine located at Site F (situated mid-river between Perch Rock and Gladstone Lock), would be able to generate an average of 20.6kW over the lunar period, which equates to an annual output of 0.18GWh. When compared to the output of 1.12GWh per year of Site 8, it is clear that Site 8 is significantly better suited for tidal power generation. This is as a result of the higher flow rates observed as well as the ability to encompass a larger diameter turbine at this location.

In order to increase the power output at Site 8, a multi-turbine array such as the one used at the Strangford Lough site could be employed (Marine Current Turbines Limited, 2016). This would effectively double the power output calculated for the single rotor turbine to 2.24GWh per year. This figure can be compared to the 6GWh per year output of the existing SeaGen turbine. The significant difference between these two outputs is due to the larger swept area and faster tidal flow observed at the Strangford Lough site. In order to assess whether a turbine will be an efficient form of power production a feasibility study would need to be undertaken to determine the cost-effectiveness.

7.3. Modelling and simulation

Through the modelling and simulation process a number of discrepancies and problems were observed due to limitations of the software or lack of available data, all of which will have had an effect on the final results.

Due to the lack of river depth data for the area between New Ferry and Runcorn, data had to be generated in order to complete the model. This initially resulted in large discrepancies between the measured and known data for each of the tidal diamond positions. Using a trial and error approach, data for this area of the model was modified, in order to change the velocity profiles of the flow to within a respectable degree of tolerance to the data supplied by the Admiralty Chart. Despite this there was still a degree of error between the data obtained from the model and the chart. If further data had been available, a more precise model could have been generated for this section of the estuary and as a result, a better comparison between the model and the actual conditions could have been achieved.

There was a discrepancy of around 0.4m between the tidal height predicted by the global tidal model and the predicted tidal height for Gladstone Lock. However, the effects of this error will have been minimized during the process to validate the model.

During the simulation analysis a problem with recirculation of the flow was identified at the entrance to the river. This phenomenon in the model was later attributed to the process of the inlet boundary conditions drying during low tide as the tide dropped below the seabed height. This occurred during low tide for a number of different tidal conditions, and led to the objective to validate the initial repot being dropped due to the turbulent results near the boundary. In order to resolve this the depth data at the entrance could have been edited however, this would have led to further disruption to the data resulting in the same outcome. Further studies could be done using data obtain from the Admiralty Chart 1951, which details the approach to Liverpool. This was not carried out in this study at it would have increased the complexity of the model pushing the 1,000 node limit imposed by the student licence for the software.

During the meshing process the shape of the riverbank was altered through the use of the redistribute vertices tool. This resulted in a rounding of the edges of the model compared to the relatively straight edges of the River Mersey. As a result of this process, there will have been a slight change in the flow characteristics close to the river banks. However, the effects this had on any of the potential sites identified was considered insignificant, since none of the turbines were situated within 200 meters of the banks.

7.4. Assumptions

The assumption that the power rating of the turbine would be limited to 2m/s was made based upon the rated power of the SeaGen turbine achieved at water speeds of 2.2m/s. However, further work will be required to identify the optimal power rating for a turbine at Site 8. This would require the undertaking of a cost-based analysis to determine whether or not the price of increasing the power rating of the turbine can be offset. It will require calculating the extra power produced while factoring in the decreased duration of time that this higher output could be achieved.

It should be noted that once the rated power of a turbine is reached, the power output is constant –providing a steady supply to the National Grid–, whereas the power produced between the cut-in period and the rated power level fluctuates over time. This results in an unsteady rate of supply and creates difficulties when exporting power to the grid.

An efficiency rate of 45% was used in order to calculate the power produced by the turbine. This value is the minimal operating efficiency associated with the SeaGen turbine. However, since its installation, advances have been made to improve tidal stream generator efficiencies and current technology is boasting of efficiencies in excess of 55%. It should be noted that there is currently no source of data to corroborate this under operational conditions. However, the potential to increase the turbine at Site 8 operating efficiency from 45% to 55% would increase the annual power output by 1.12GWh to 1.37GWh a year.

8. Conclusion

There is the potential to produce a minimum of 1.12GWh per year from a 17.2m single rotor turbine at Site 8 with the potential to double this to 2.24GWh through the uses of a multi turbine array. However due to its location in the centre of one of the busiest sections of the river estuary, it is unlikely that a turbine will ever be situated in the River Mersey at this site, due to the increased risk that it would pose to marine traffic in the area.

Acknowledgments

The authors would like to thank DHI for granting access to the MIKE 3 software and John Carrier for providing technical comments. The authors would also like to thank Liverpool John Moores University and Royal Academy of Engineering for financially supporting this study.

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