# Numerical modelling of the response of tidal resonance to the presence of a barrage

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## Abstract

A tidal energy barrage has been proposed for the Severn Estuary, UK. In order to predict the effect such a structure may have on the tidal resonance in the channel, a simple two dimensional model has been developed for a series of simulated estuaries, ranging from a simple box channel with a uniform flat bed to a simple wedge shaped channel with a solid barrier across, to a simulation of the Severn Estuary with topographic and bathymetric values. These modelsshow amplitudes and phases of elevation and current flow for each model scenario. model outputs show that overall tidal resonance decreases with the construction of a barrier across a channel.

**Keywords:** Resonance, tidal barrage, tidal energy.

## 1 Introduction

Marine energy is becoming an increasingly viable option within the field of renewable energy due to its reliability, predictability and the size of the resource. Government commitments to reducing carbon emissions and the general use of pollutant gases, a declining carbon based energy resource, a likely future increase in energy demand and an uncertain security of global supply of more traditional energy sources ensure that renewable energy alternatives are increasingly viewed as feasible options.

Tidal energy specifically has been used since Roman times [1] and its combined reliability and predictability help establish the place of both tidal stream and barrage power generation within future plans for marine renewable energy development. A tidal energy barrage creates a permeable structure across an estuary and contains a number of sluice gates and turbines which are located within the passage of the water, this converts the potential energy, which is stored within the different levels of water across the barrage system, into kinetic energy in the form of flowing water, this kinetic energy is then converted into electricity for transmission [2].

Energy generation on the ebb tide is the economically preferred mode of operation within a barrage [3] and consists of allowing water into the basin through the sluice gates on the flood tide where the water is then held until a body or head of water is created. This water is then emptied through the turbines towards the sea on the ebb tide, continuing until the seaward water level reaches the minimum operating level where it is then held until the flood tide can then repeat this process [4].

The high tidal range required for the extraction of tidal energy by a barrage occurs within an estuary due to the shelving of the seabed, tidal resonance and funnelling of water [4]. Tidal resonance occurs when the time taken for a large wave to travel from the mouth of the bay to the opposite end of the estuary, is then reflected and travels back to the mouth of the bay and coincidentally matches the time from one high tide to the next. Where this then meets with the next tidal wave an increase in tidal amplitude can occur [5]. Resonance is present within the Bristol Channel in the South-West of England and is reinforced by funnelling as the tidal wave travels up the estuary where it narrows and the wave crest length shortens and the height increases, therefore increasing the energy density [6].

The Severn Estuary / Bristol Channel has been proposed as a suitable barrage location due to it having the worlds second largest tidal range which can reach up to 14 metres on a spring tide [7]. In order for a barrage to be efficient and cost effective, the tidal range has to be substantial, and it has been suggested that within the UK it is not financially viable to construct a barrage in an area where the tidal range is anything less than 5 metres [8].

A barrage within the Severn would effectively block off the estuary converting it in to a hydroelectric dam [9], generating the equivalent energy output as 2-3 major thermal power stations [10]. The Severn Barrage project has been proposed and rejected several times over a number of years with the first official government studies coming from the Bondi Committee report in 1981 and the Department of Energy, Central Electricity Generating Board and Severn Tidal Power Groups report, The Severn Barrage: General Report in 1989 [11]. Discussions have recently resurfaced due to pressures brought on by climate change issues and security of supply prompting the Sustainable Development Commission report Turning the Tide in 2007 [11] and the Department of Energy and Climate Change document Severn Tidal Power, Phase One Consultation in January 2009 [12] both of which review the feasibility and challenges relating to the project and have selected the route from Cardiff to weston Super Mare as one of the most popular sites for barrage placement..

The worlds largest operating tidal barrage, La Rance is located in north-western France and was constructed in 1966 in order to help supply electricity specifically to the Brittany and Normandy regions [13]. Other operating barrages include Annapolis Royal in Canada and Jiangxia Creek in China, with construction currently taking place on the Shiwa barrage in South Korea and proposals coming forward in the UK for tidal energy barrages in the rivers Mersey and Dee, the Solway Firth and Morcambe Bay. Although lessons can be learned from established barrages they should not be relied on for accurate evidence as to how each estuary will react as the design and environmental impacts of a barrage are primarily determined by the individual site specifications and barrage design [4].

Although tidal barrages are a secure and predictable source of energy, they are currently a highly controversial option. The high capital cost, lengthy construction times and environmental implications ensure that public, scientific and political opinions are divided leading to a low uptake of the technology [8]. Plant location should be dictated by potential environmental consequences, the feasibility of construction, basin closure and the size of the tidal range. Tidal power projects are generally highly capital intensive, have extensive construction times and often require grid upgrades and strengthening (however, few sites worldwide have a tidal range large enough for energy production in close proximity to electricity users and the transmission grid as within the UK). This leads to high interest costs and high unit cost per installed kilo watt with not all benefits of the barrage being accrued to the developer therefore creating reluctance to initiate development [14]. The Sustainable Development Commission has recommended that a structure the size of the proposed Severn Barrage could not feasibly be funded by the private sector and therefore the government should lead the financing with input from other public and private sources [11].


**Figure 1:** Geographical map of Bristol Channel Study area (not to scale).

The construction of a barrage is likely to affect numerous stake holders and user groups including commercial shellfish / fisheries, recreational users, industry, general ecosystem conservation and shipping therefore necessitating a coordination of all objectives [15]. However, barrage construction poses an opportunity within many communities to create a new industry (with the potential creation of numerous jobs), and as in Cardiff Bay [16] a barrage could potentially be a catalyst for economic, environmental and social regeneration as well as giving the primary benefit of electricity generation. A report by Taylor [14] states that there is ‘no other source of renewable energy which has the scale, reliability and predictability or proven technology of tidal power from the Severn, nor make the same contribution to security and diversity of supplies from a single project,’ and in relation to coal fired generation the energy generated by the Severn Barrage would avoid the emissions of 18 million tonnes of carbon dioxide per year (4.6 million tonnes of carbon) which is 3% of the UKs carbon emissions from all sources and in comparison to gas fired generation the saving would be 3.1 million tonnes of carbon [14]. However, despite the advantages that a tidal barrage would create, there is a requirement to keep all alterations to the environment and tidal system to a minimum whilst still being able to tap the tidal system for energy [17].

## 2 Case Study Site Description

The Severn Estuary has a 14 metre tidal range and is flood dominated with higher incoming currents than on the ebb [7]. The estuary tides are dominated by the principle lunar semidiurnal M2 constituent with a tidal period of 12.42 hours. Table 1 shows tidal amplitudes and phase variations through the Severn Estuary.

| Location | Amplitude (m) | Phase (°) |
|---|---|---|
| Swansea | 3.14 | 173.2 |
| Ilfracombe | 3.08 | 161.7 |
| Newport | 4.13 | 198.0 |
| Avonmouth | 4.22 | 201.9 |
| Cardiff | 4.09 | 197.0 |
| Flat Holm | 4.00 | 192.0 |

**Table 1:** Tidal constituents for the Bristol Channel.

The Bristol Channel has some Atlantic swell waves at the mouth though these do not travel as far as the estuary where wind waves mix with tidal currents, therefore causing shorter and steeper waves to occur [7]. The Bristol Channel is characterised by a high suspended sediment load which has been stripped from the channel bed leaving bare rock. This then forms deep layers of fluid mud which settles on the spring tide [7]. The Severn Estuary is primarily erosional with accretion taking place only at some of the coasts, this may be altered if a barrage is constructed due to a reduction in turbidity and suspended sediment [18]. There are a range of sediments within the estuary including organic material, peat, gravel, sand, silt and clay [15] which encourages colonisation of algae and invertebrates within the finer sediments which have settled from the water column (depending on wave and current action) [19]. Due to the accretionary nature of the coastline, mud generally overlies sands producing extensive intertidal areas of salt marshes and mudflats [7]. The construction of a barrage would see the loss of up to 14,428ha in intertidal areas around the Severn Estuary [11].

The morphology of the estuary has altered over the last century due to the construction of sea walls and a rise in mean sea level [15]. It is predicted that without barrage construction within the next hundred years the wide intertidal areas may have disappeared entirely due to the increase in the rate of sea level change [15]. However, this process would be brought forward by the construction of a barrage by increasing sea level and reducing tidal range and currents landward of the wall almost instantly. This would also cause reduced dispersion rates of effluent and reduced turbidity, potentially causing an increase in bacterial decay rates due to greater UV penetration (with decreased turbidity) and a smaller variation in salinity per tidal cycle [18].

The development of the proposed barrage within the Severn would have a lead construction time of up to 14 years with 5-7 years of environmental impact assessment and engineering design studies prior to this [9] before any energy generation could take place. This could potentially cause large problems for funding the project as financial institutions may find long construction times and overall public and political uncertainty in opinion off-putting, therefore causing financial organisations and developers to request the costs to be underwritten by the government for preconstruction work, as recommended by the Sustainable Development Commission [11].

## 3 Hydrodynamic Model

The 2-dimensional 'Tidal Flow Development' (TFD) numerical model was used to build up several simple grid systems of simulated estuaries with a variety of boundary and bathymetric conditions. The model, originally developed at the University of Strathclyde, solves conservative forms of the Shallow Water Equations (see equations 1, 2 and 3).

$$\frac{\delta\eta}{\delta t}+\frac{\delta(Uh)}{\delta x}+\frac{\delta(Uh)}{\delta y}=0 \tag{1}$$

$$\frac{\partial(Uh)}{\partial t}+\frac{\partial(UUh)}{\partial x}+\frac{\partial(UVh)}{\partial y}=fVh-gh\frac{\partial\eta}{\partial x}
-gn^2\frac{U\sqrt{U^2+V^2}}{h^{\frac{1}{3}}}+\left(\frac{k\sqrt{gn}\sqrt{U^2+V^2}h^{\frac{5}{6}}}{6}\right)
\left[2\frac{\partial^2 Uh}{\partial x^2}+\frac{\partial^2 Uh^2Vh}{\partial y^2}+\frac{\partial^2 Vh}{\partial x\partial y}\right] \tag{2}$$

$$\frac{\partial(Vh)}{\partial t}+\frac{\partial(UVh)}{\partial x}+\frac{\partial(VVh)}{\partial y}=fUh-gh\frac{\partial\eta}{\partial y}
-gn^2\frac{V\sqrt{U^2+V^2}}{h^{\frac{1}{3}}}+\left(\frac{k\sqrt{gn}\sqrt{U^2+V^2}h^{\frac{5}{6}}}{6}\right)
\left[2\frac{\partial^2 Vh}{\partial y^2}+\frac{\partial^2 Uh^2Vh}{\partial y^2}+\frac{\partial^2 Uh}{\partial x\partial y}\right] \tag{3}$$

A simple grid system was used whereby simulated estuaries were created and built up ranging from a simple box channel with a north and south boundary and uniform flat bed to simulated Severn estuary with topography shape and bathymetric values taken from local Admiralty Charts. Each grid square has a cell size of 750m and covers an area of 109.5 x 39.75 metres within the Severn Estuary area. The origin was at Ilfracombe / local UTM (Universal Transverse Mercator) coordinates 412635.59W, 5670955.15N (51°11'00'N, 4°15'00'W), Table 2 describes each grid specification.

The model uses an explicit scheme and therefore applies the Courant Friedrich Lewy (CFL) stability criterion $CFL=(gh)^{0.5}\frac{\Delta t}{\Delta x}<1$ where g is the acceleration due to gravity, h is the mean water depth, t the time step and x is the grid spacing. A CFL<0.5 was required in order to ensure stability when strong nonlinear effects occur. A time step of 10 was used and a simulation time duration of 540000 seconds (150hrs, approximately 12 M2 tidal cycles). However, graphed data in this paper only shows the last 270000 second (75hrs) in order to avoid any potential noise or inaccuracies developed during the spin up period. Driving boundary conditions were taken from Ilfracombe on the south-west coast of the estuary, with a tidal spring elevation height of 4 metres and a neap elevation of 2 metres, with a local mean sea level of 5.04 metres. A no-slip land boundary was input to simulate realistic friction conditions at the coastline and a Manning number of 0.025 as sandy bottom type.

### 3.1 Modelling Results

Each grid was run with the specifications listed in Table 2 with both simulated spring and neap tidal conditions, with tidal curves being created at three points (the open, middle and close centre line points) for each grid except Grid 6 which contains the barrage and has only data from the open and mid curves.

| Grid | Specifications |
|---|---|
| Grid 1 | Basic box shape (147 x 53 cells), land running along top and bottom of domain, no end boundary, uniform flat bottom of 35m. |
| Grid 1B | Same as Grid 1 with varied bathymetry of ranging from 60m at the open boundary to 10m at east edge of domain. |
| Grid 2 | Basic box shape (147 x 53 cells), land running along top, bottom and end edges of domain, uniform flat bed of 35m. |
| Grid 3 | Same as Grid 2 with varied bathymetry ranging from 60m at the open boundary to 10m at closed boundary. |
| Grid 4 | Basic channel shape wedge (open boundary 51 cells x closed end boundary of 3 cells), uniform flat bed of 35m |
| Grid 5 | Same as Grid 4 with varied bathymetry ranging from 60m at the open boundary to 10m at closed boundary. |
| Grid 6 | Same as Grid 5 with simulated barrage across channel crossection at line 98 blocking off inner channel of estuary. |
| Grid 7 | Same as Grid 5 with open channel at the east edge of the wedge domain. |
| Grid 8 | Topography of Severn Estuary coastline with flat uniform bed of 35m. |
| Grid 9 | Same as Grid 8 with baythymetry of Severn Estuary. |

**Table 2:** Modelling scenarios used to show the influences on a resonant tidal system.

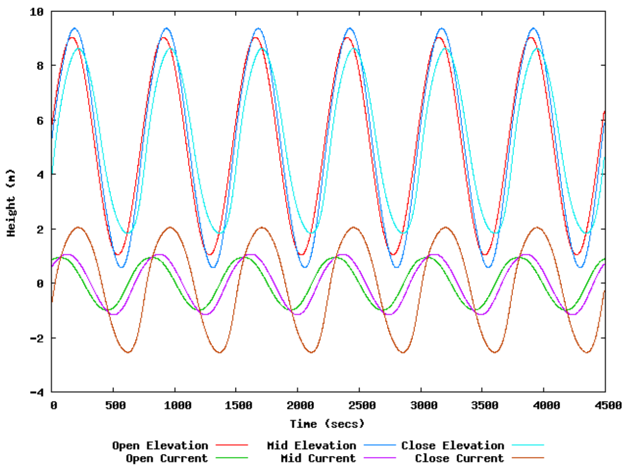


**Figure 2:** Mid channel surface elevation and depth averaged current velocity (streamwise component) for Grid 1B on a simulated spring tide.

Figure 2 shows that the tidal elevation decreases with distance from the estuary mouth and tidal curves become out of phase therefore showing no resonant characteristics, however the current velocities do double between the open and close part of the channel from a height of 1m to 2m and by the close of the channel the current velocities become in phase with the elevations. This is potentially due to the smooth nature of the coastline exerting a reduced amount of friction on the water body, therefore encouraging an increase in current velocities through the channel.

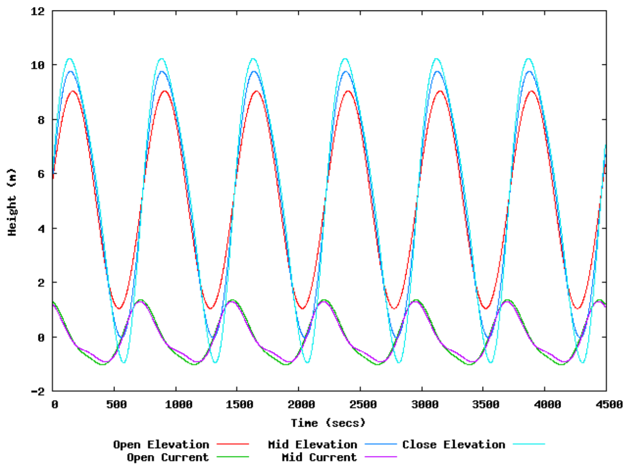


**Figure 3:** Mid channel surface elevation and depth averaged current velocity (streamwise component) for Grid 3 on a simulated spring tide.

There is some evidence shown in Figure 3 that this system is resonating with the overall increase in tidal elevations with distance from the mouth of the estuary to the head of over 1m on the flood tide and 2m on the ebb tide and tidal curves remain in phase throughout the system. The current velocities have a lag behind the elevation phase of up to a quarter wave length but do stay in phase with each other. This system is resonating more than that of Grid 1B in which there is no easterly boundary to the domain. This suggests that the inclusion of a landward boundary helps to increase resonance within a channel by acting as a reflective barrier.

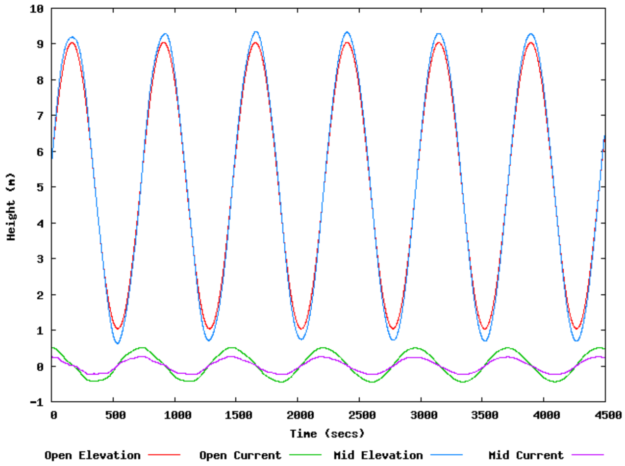


**Figure 4:** Mid channel surface elevation and depth averaged current velocity (streamwise component) for Grid 6 on a simulated spring tide.

Figure 4 show that the system is resonating slightly with a small increase in tidal elevations with distance from the mouth of the channel. However, tidal current velocities decrease with distance from the channel mouth in contrast with most of the other simulations where current velocities have increased overall by the time they have reached the closed point of the channel. This is potentially due to the barrier causing an overall reduction in current velocities.

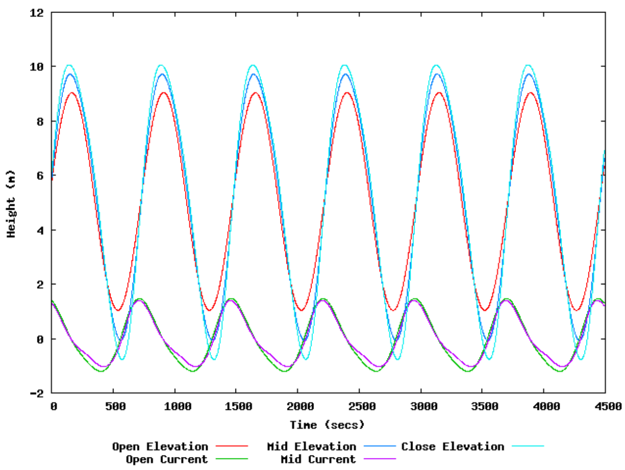


**Figure 5:** Mid channel surface elevation and depth averaged current velocity (streamwise component) for Grid 8 on a simulated spring tide.

The system shown in figure 5 exhibits perfect resonance with the increase of up a metre of elevation from the open part of the channel to the upstream closed section with all tidal waves staying in phase with each other. Current velocity remains at a stable level throughout the domain and does not increase with distance from the mouth as with other simulations. This is possibly due to the nature of the flat sea bed which does not cause any change in velocity through the channel as a varied bathymetry can do by increasing the amount of energy held within the body of water.

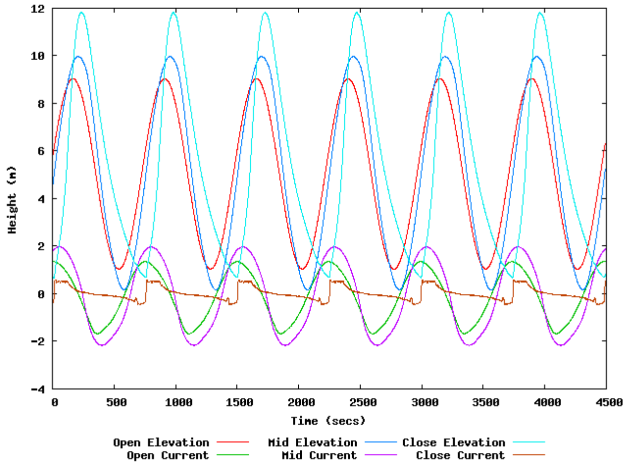


**Figure 6:** Mid channel surface elevation and depth averaged current velocity (streamwise component) for Grid 9 on a simulated spring tide.

This simulation shown in figure 6 exhibits a large increase in elevation through the channel, which becomes out of phase by up to a quarter wave length. Current velocities increase throughout the channel with some non-linear effect at the close of the channel potentially caused by intertidal areas where the model has some difficulties dealing with periods of wetting and drying, or due to a reduction in channel crosssection further upstream.

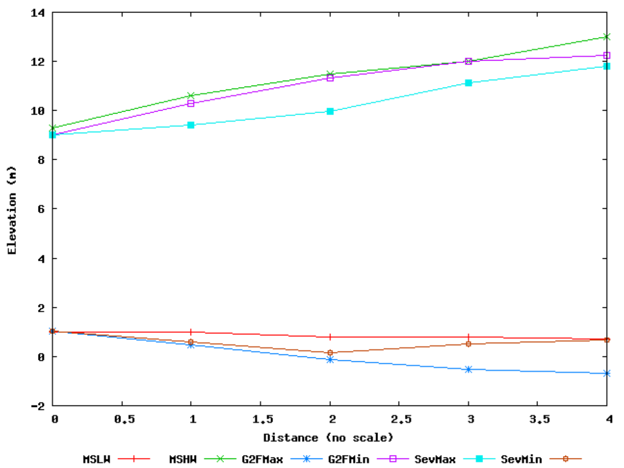


**Figure 7:** Tidal elevation maximum and minimum heights at five arbitrary points along the channel in an west to east direction with (MSLW) observed mean spring low water, (MSHW) observed mean spring high water, (G2FMax) Grid 2 maximum, (G2FMin) Grid 2 minimum, (SevMax) Grid 9 maximum, (SevMin) Grid 9 minimum.

When examining variations in tidal elevations between observed Admiralty data and modelled results (see figure 7) it is clear that the maximum values match to within a metre of each other, and the simple box model and the observed data are closer than the modelled Severn Estuary elevations. However for the minimum values the observed tidal elevations are closer to the Severn Estuary model than the box model by up to one metre. This shows that the model over resonates on the neap tides more than on the spring but overall the model is shown to be effective at gaining results close to the observed data.

In reality a fully operating tidal barrage is not simply a solid barrier across a channel, however in this situation it has been modelled as so in order to avoid the difficulties of modelling a permeable barrage in which energy is extracted, and this model simply acts as a guide to how tidal characteristics would respond to being blocked off by a solid barrier. By modelling the difference between the estuary with and without a barrage it allows us to see the response of the estuary with no permitted flow through to the head of estuary. Any resonance should act to increase tidal amplitude and this model has demonstrated that overall tidal resonance in channels without a barrier is between 1-3 metres but where a barrier exists this is reduced to approximately 0.25metres, and therefore it can preliminarily be concluded that resonance in an estuary is reduced by the construction of a barrier.

## 4 Summary and Conclusions

There is an observed difference in tidal amplitudes and phase between the north and south coasts of the Severn Estuary. Due to this, future analysis should use a centre line elevation estimate derived from the average observations from both coast rather than just one, as was the case within this research for Ilfracombe. Future work should also include extending the boundary conditions further offshore, as Ilfracombe is potentially too close to the barrage site to be a suitable input location for forcing conditions, as the Severn Barrage may potentially have a large impact some distance from itself and therefore if the boundary is too close the impact of the barrage will not be correctly modelled. Another limitation of using the one boundary input condition is that this gives a fixed input elevation across the mouth which is not necessarily an accurate representation.

It is acknowledged that the Severn Estuary and River Severn extend beyond the eastern landward boundary for the model and in reality any upstream components will have an influence on the system, this has been represented to a small degree with the difference in wedge models that have a closed (Grids4-5) and open head (Grid 7). However this does not include any freshwater input from the east direction into the estuary as would occur in the physical environment.

There are a number of challenges which present themselves when attempting to model such a large and complex system like the Severn Estuary. These can include: amplitude towards the head of the estuary not being solely due to resonance but potentially from a concentration of tidal energy in response to a changing channel cross-section, the M2 tide can only be used as a guide to spring and neap variations and not as an accurate representation of tidal elevations in the area, and the difference in tidal amplitude and phase for each location throughout the Severn Estuary and the ability to match this to the model data is not always possible.

Examining the Severn Estuary in isolation without the inclusion of the full Bristol Channel through the Celtic Sea to the shelf edge may omit some deep ocean tidal forcing factors which in future work needs to be addressed. In order to accurately model the interaction and observe any changes due to the presence of a barrier the whole shelf system needs to be modelled as the resonance observed in the Severn Estuary and Bristol Channel are related to distance from the shelf edge.

Although to a certain extent boundary condition dictate results within the model, as a basic indication as to how the Severn Estuary would behave with the introduction of a barrage, this model has served well and with the development of each estuary scenario with the the grid format it is easy to see the progression of tidal amplitude, phase and velocity from a basic box channel to simulated Severn Estuary with real topography and bathymetry, therefore realistically modelling the hydrodynamics and demonstrating the variations in energy dissipation and flow throughout the system, and demonstrating that the inclusion of a solid barrier or barrage into the Severn Estuary will act to reduce tidal resonance.

The simple two-dimensional model being used within this paper is being employed as a fore-runner to a build up of comparisons with other more complex models such as the Regional Oceanic Modelling System (ROMS) which will examine ecological, sedimentary and hydrodynamic impacts of the proposed Severn Barrage.

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