Mapping the Unresolved Tidal Resource in Estuaries

M. Lewis , D. Khojasteh, G. Iglesias, P. Evans and S. Neill

Abstract— **Estuarine geometry often amplifies the tidal range. Tidal amplitude can be amplified in an estuary due to three processes: shoaling and funnelling of tidal energy flux, and, when estuary length-scales are close to the tidal period, tidal-wave resonance. The amplification of the tidal energy resource (via increased tidal amplitude and associated currents) is juxtaposed to areas of high electricity demand (industry ports and residential areas), and yet the tidal resource of many estuaries is unknown due to computational difficulties. For example, a bespoke high-resolution hydrodynamic models of every estuarine system globally is not possible; instead, a simple set of rules to focus resource mapping efforts may be suitable approach. Indeed, given that significant changes to estuarine tidal dynamics can occur within the life-time of some tidal energy developments (due to the balance between the tide and river-flow climatology, sea level rise and sedimentation). We aim to develop a simple approach resolve the global estuarine tidal energy resource and how this may change within the coming century. A simple 1-D analytical model is presented, which can account for the major physical processes of estuarine tidal amplification. We find changes to estuarine tidal dynamics within the lifetime of a development should be considered, both for resource mapping and annual yield assessment, but also within the baseline scenario in assessing the environmental impact of a development (i.e. should changes to the estuary be based on present day or 2100 tidal dynamics?).**

Keywords— **tidal energy, resource, estuaries, climate change, modelling**

I. INTRODUCTION

ESTUARIES typically have high tidal ranges and strong tidal currents, due to amplification processes; and this resource is juxtaposed to urban areas with electricity demand [1]. For example, 22 of the 32 largest cities in the world are adjacent to estuaries [2], and UK estuaries collectively worth over £5.5b to UK economy with >1/6th of the population and ~1b tonnes of cargo traded at their ports [3]. To date, much oceanographic research has rightly focused upon estuarine flood risk and impact to port activities (e.g. [4]; however, we feel it is timely to revisit estuarine tidal energy - given the public's desire for renewable energy sources and the recent NASA Satellite Water and Topography satellite (SWOT: https://swot.jpl.nasa.gov/) that has an objective of mapping of hydrodynamics at a spatial resolution useful for a global resource assessment (10m to 70m swath that can resolve estuarine water-level height differences don to 0.1m).

Mapping the tidal energy resource is challenging as the simulated current speed is sensitive to ocean-model resolution [5]. Furthermore, both tidal amplitude and currents are heavily modified in estuaries [6]; therefore are bespoke and high-resolution hydrodynamic models needed to resolve the tidal energy resource in each estuarine system of the world? Whilst many estuary-specific resource modelling studies have been achieved (e.g. [7]), no large-scale future tidal energy resource mapping project has been undertaken – likely due to computational cost (e.g. [5]).

It is therefore unrealistic to hydrodynamically model all global estuarine systems, to resolve current and future changes to the tidal energy resource; instead, we aim to develop a simplified method to estimate estuarine tidal energy resource. Furthermore, estuarine tidal dynamics have been observed to rapidly change in response to altered river-flow climatology or changes to bathymetry and morphodynamics (e.g. dredging); see [4]. Given climate models predict future changes to river-flow climatology and mean sea-level rise projections – we aim to develop a simplified analytical solution to map the estuarine tidal energy resource and compare to potential changes in the resource within the lifetime of a

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development.

Tidal-stream energy converts the kinetic energy of strong tidal currents (>2 m/s) into electricity (see [5]), and many estuaries tidal stream energy sites have been reported as potentially economically viable (e.g. [7]). Tidal range energy schemes are currently only considered economically viable if the mean tidal range is greater than 5m, thus M2 amplitude >2.5m (e.g. [8]). The present engineering approach for tidal range energy schemes in estuaries are "barrages", which provide a barrier between the ocean and estuary. Using sluice gates and turbines, the water-level can be artificially held at high or low tide, creating potential energy as the water level difference increases between the ocean and estuary during an ebbing tide or flooding tide, or both. Two very good reviews on tidal range energy schemes have been published recently: Neill et al. [9] and Waters and Aggidis [10]; we therefore direct the reader to these studies and instead focus on the impact of future physical changes to resource, namely Mean Sea Level Rise (SLR).

Recent probabilistic assessments suggest a global sea-level rise of 0.3–1.3 m by 2100, though high-end scenarios suggest a rise of ~2 m could be likely [4]. The impact to global tides is known to be problematic [11], due to uncertainties in model parameterisation of the coastline as well as spatial variability in sea-level rise and tidal dynamics. Nevertheless, 10% changes to the major semi-diurnal lunar constituent appear possible in shelf sea systems [12]. Tidally-dominated estuaries will adapt to rises in mean sea level, as the balance between tidal dynamics, estuarine morphodynamics and river flow climatology is altered. We therefore hypothesise the tidal energy resource within estuaries is likely to change within the coming century.

The impact of sea-level rise and changes to estuary dynamics is therefore of great interest to tidal energy developers and coastal areas with renewable energy ambitions (especially as estuarine systems often enhance the tidal range). Three physical processes drive mean tidal range amplification (i.e. if we exclude overtides): Funnelling, resonance and shoaling (see [13]). We shall detail these three processes first, and then examine theoretical sea-level rise modification to tidal range energy resource in inlets, deltas and estuaries (due to changes in physical processes that drive tidal amplification); before then exploring numerical model simulations and observations to future tidal dynamics as well as uncertainties.

II. Physical processes of estuarine tidal modification

Friction affects tidal wave propagation landwards, along the estuary length. The impact of friction will alter tidal height, and thus tidal range, landwards along an estuary due to continuity (phase-speed of the wave slows, resulting in an increase of wave height). The amount of tidal range amplification will be specific to estuary shape and size (e.g. narrow mouth or wide mouth), as well as tidal-energy is concentrated and the tide is "funneled" This interplay between tidal dynamics and sediment transport pathways, will alter the morphology of an estuary (as often large volumes of sediment reside within a estuary). We therefore explore each physical processes in a simplified manner to inform our discussion and literature review.

A. Resonance

Resonance occurs when basin length-scales (x) are such that the natural period of the basin (T) matches the wavelength (or product of) the tidal wave-length (L). The tide travels as a shallow-water wave, with the phase-speed considered as the travel of HW along an estuary length; therefore resonance of an inlet or estuary can be modified not just be estuary shape (thus length) but also changes to bathymetry (i.e. dredging or sea level rise). The impact of sea-level rise of the resonance length-scale for a simple, single harmonic tide of period 12.42 hours (i.e. the major semi-diurnal lunar constituent, M2) is demonstrated in Figure 1a, based on the 'Merian's Formula' [Eq. 1] where the natural period (T) is a product of the mode of oscillation (where n is number of nodes) and the shallow water wave speed thus:

$$T = \frac{2nL}{\sqrt{gh}} \quad (1)$$

As T = 12.42 hours, the impact to L from a mean sea-level rise (SLR) of 1m and 2m can be analytical solved. If depth (h) is assumed to be uniform and constant, then L~250km for resonance to occur. If we add 1 and 2m SLR respectively, then the resonant basin length for an M2 tide (L) increases by ~1% - whilst in shallower systems the effect is greater: 30m deep estuary resonant length changes by 1.5% and ~4.5% resonant length change for 10m deep estuary. Therefore, as shown in Figure 1a, in shallow and long estuaries close to resonance length scales (~250km) significant changes to the tide could occur by 2100 (due to Sea Level Rise alone).

B. Shoaling

Shoaling is typically used to describe the physical process of waves approaching a shore: The reduction in water depth (h) results in an increase to wave height (H), relative to the deep water wave height (H_0), as wave-energy propagation is reduced due to friction and conservation of energy. If we assume no energy loss from

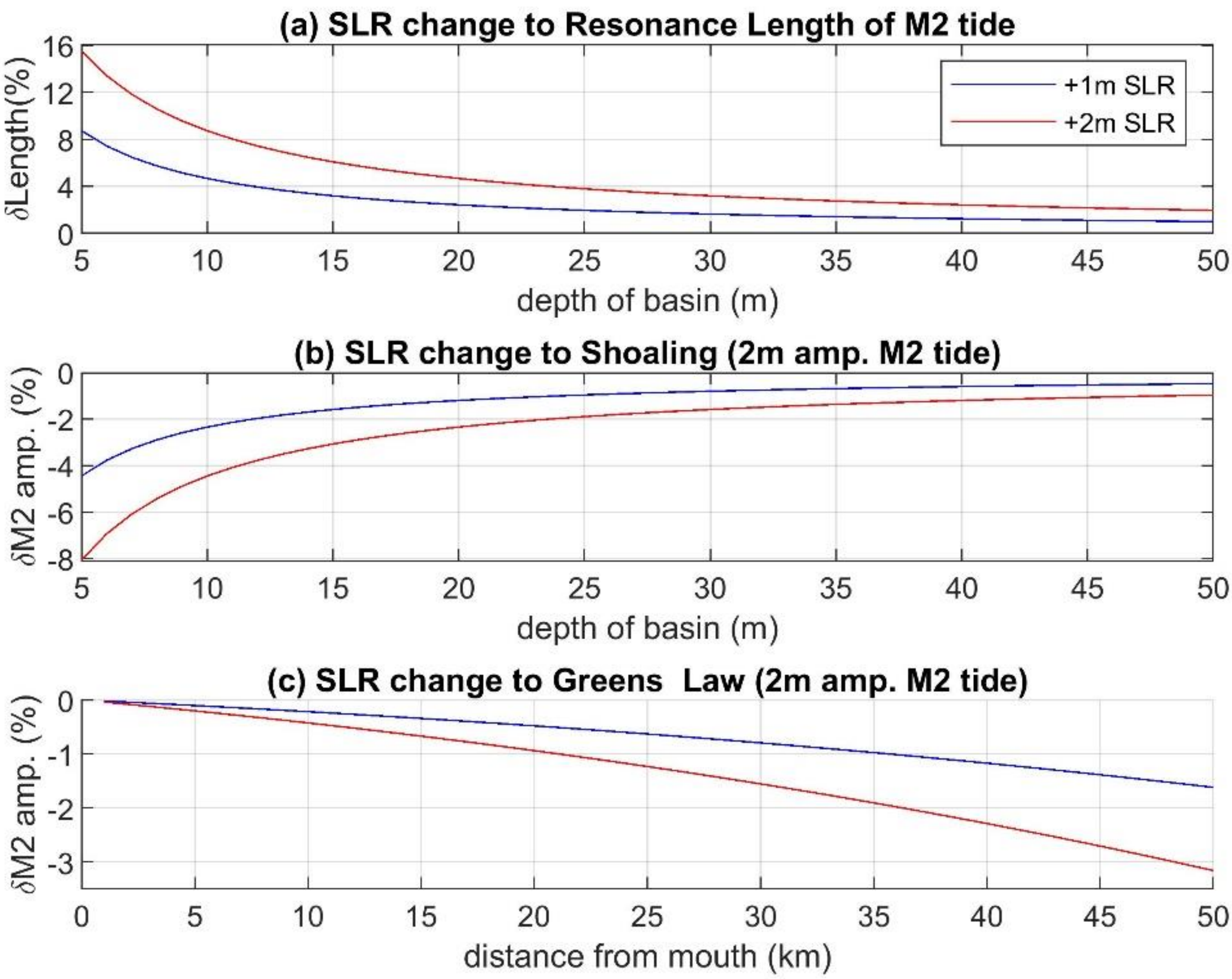

Fig. 1. The impact of sea-level rise (SLR) to three main drivers of tidal amplification in estuaries in simplified analytical form, assuming no morphodynamical feedbacks constant water depth and a simple M2-only tide; where tidal dynamics are solved analytically for a 2m amplitude tide (with a period of 12.42h) .

friction, the relative wave phase speed (*c*) and wave number (*k*) can estimate the analytical increase to wave height (H/H_0), as detailed in Pond and Pickard [14] in Eq. 2, where sub-script $_0$ denotes deep water wave properties, thus:

$$\frac{H}{H_0} = \sqrt{\frac{Ec}{E_0 c_0}} = \sqrt{\left({}^{c}/_{c_0}\right)\left(1 + \frac{2kh}{\sinh 2kh}\right)} \qquad (2)$$

The shoaling process can also modify the tidal elevation in long shallow inlets, and in extreme cases result in the phenomena of tidal bores (e.g. [12]). Here, we use the principles of Eq. 2 to explore the impact of sea-level rise to tidal amplification due to shoaling in Figure 1.2; and demonstrate that SLR could reduce tidal amplitude as the processes of shoaling is reduced; however no interaction with estuarine morphology is considered.

C. *Funnelling*

The concentration of the tidal energy flux, as the tide propagates towards areas of reduced width, also increases tidal amplitude. To estimate the increase in tidal amplitude, continuity can be solved if the change in tidal wave speed along an estuary length is included. Therefore amplification is dependent on water depth (γ = 1/h) and shape, including width (β = 1/width), and typically requires a computational model to solve. However, neglecting friction and assuming constant depth, gives a simplified analytical solution called "Greens law" is detailed in van Rijn 2011 [15].

$$\frac{H}{H_0} = e^{(0.5(\beta+\gamma)x)} \qquad (3)$$

Therefore Eq. 3 describes how the tidal height increases exponentially for exponentially decreasing width and depth. Assuming no morphodynamical feedbacks, constant bathymetry of 50m (and 45km length of estuary) and no frictional effects; the reduction in "funnelling" amplification of the tide due to SLR is clearly shown in Figure 1.3.

III. SEA-LEVEL RISE IMPACT TO COMBINED TIDAL AMPLIFICATION PROCESSES

The sensitivity of tides in estuaries to Sea Level Rise (SLR) is demonstrated in Figure 1, due to the changing of water depth and therefore the phase-speed of the High Water bulge (i.e. wave crest). The combination and interaction of the three physical processes in Figure 1 is not clear, requiring a numerical ocean model. A simplified 1D shallow water equation model is applied to resolve the interaction of these three physical processes in estuarine tidal amplification. Assuming conservation of mass (Eq. 4) and momentum (Eq. 5), the cross-sectional area of the estuary (A) is solved with estuary width (B) and elevation (η), width-averaged velocity (U) for each discretised grid point (∂x), water depth (h) and friction (Cd).

$$\frac{\partial \eta}{\partial t} = -\frac{1}{B}\frac{\partial (AU)}{\partial x} \tag{4}$$

$$\frac{\partial U}{\partial t} = -\frac{\partial \eta}{\partial x} - \frac{Cd\,U^2}{(h+\eta)^{4/3}} \tag{5}$$

The simplified 1D numerical model of Equations 4 and 5, have been shown effective in many estuaries including the Bristol Channel – a site of a large tidal range resource [13]. Using these Bristol Channel dimensions (see [13]), we can evaluate our discretised 1D shallow water equation model and demonstrate the application: assuming an estuary Length (L) of 170km; with a discretisation of ∂x ~3.86km; time-step (∂t) of 29s; width of 140km at mouth (L=0) converging at 44.8° in a triangular shape with constant water depth of 20m and a simple 12.42 hour period tide (i.e. M2 tide only) with an amplitude of 1.5m at the open boundary (where L=0). The simulated tidal elevation of the simplified Bristol Channel tide is doubled to ~3m along the estuary (Figure 2), which is also reported by Neill et al. [13].

Sea-level rise was added by increasing the water depth (h) by 1m and 2m respectively (see Figure 2a), throughout the domain. Spatially varying changes to the tidal amplitude along the estuary length – but an overall decrease in tidal height was simulated (Figure 2a), with increasing effect along the estuary length (i.e. as L increases). The processes involved in the amplification of the tide within estuaries are therefore sensitive to Sea-Level Rise, because changes to water depth will alter the tidal-wave propagation speed; affecting funnelling, shoaling and the natural period of the estuary.

Mean Sea-Level rise will also affect shelf sea tidal dynamics (e.g. [12]), which will alter the tidal amplitude at the estuary mouth. The impact of increasing tidal amplitude by 10% at the model boundary (L=0), shown in Figure 2b as the dashed lines. Indeed, a 10% increase at the tidal boundary of Figure 2 had a bigger impact (to peak tidal elevation along the estuary length) than the mean sea-level rise scenarios – which has clear implications for mean sea-level rise impacts to shelf sea tidal systems (and thus the tide propagating into an estuarine system).

In the simplified Bristol Channel geometry simulation of Figure 2, the tidal energy resource is reduced with sea-level rise, with a 2m mean sea-level increase requiring a ~10% increase in tidal height at the estuary mouth to counter-act the decrease. The result shown in Figure 2 would differ for a different shaped estuary and water depth, however figure 2 does demonstrate the interaction of the three physical processes involved in estuarine tidal amplification, and that changes to the tidal along an estuary could be non-linear. Therefore, the interaction of sea-level rise, tidal dynamics, and mobile sediment makes the morphodynamical and tidal range resource response specific to every estuary. Simplified solutions to estuarine tidal dynamics have been shown useful (e.g. [6], [15] and [17]), as is also demonstrated in this paper. Hence, individual estuary response to SLR needs location-specific modelling; in particular, the morphodynamical response and interaction with an estuary system [18]. What should be clear, from our simplified analytical and numerical solutions of Figure 1 and Figure 2, is that the tidal amplification that occurs in some estuaries appears sensitive to estuarine geometry, and therefore coastline changes (e.g. Shoreline Management Planning and flood risk strategy) and sea-level rise are likely to change the present tidal energy resource of estuaries within the coming century.

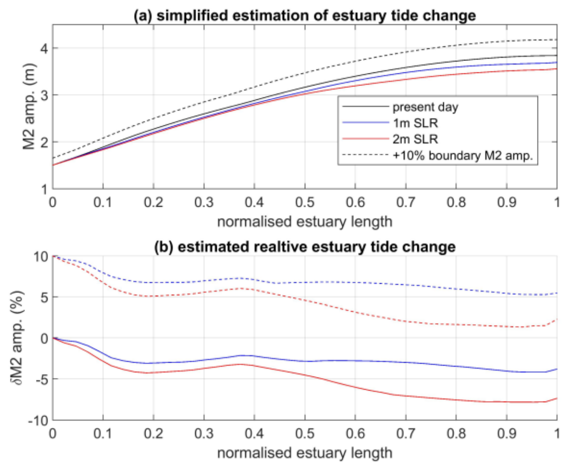

Fig. 2 Numerically simulated impact of tidal amplification on the major lunar semi-diurnal harmonic constituent (M2) in an idealised estuary, shown in panel (a), and the relative change to tidal amplification (δM2) shown in panel (b) for 1 m and 2 m of SLR – with the impact of a 10% change in the M2 amplitude at the estuary boundary shown with a dashed line.

It has been estimated that the major semi-diurnal major constituent of the tidal elevation (M2) has increased by approximately 1% per century In Brest, France [4]. Channel deepening has amplified tidal range throughout the Scheldt and Ems estuary, with an approximately 1 m increase in tidal range near the upstream boundary since 1900 (see [4]). In a recent modelling study of specific estuaries on the East coast USA, sea-level rise was found to increase the tidal range (thus resource) with coastal flood management crucial to the increase of tidal range [19] – with implications to tidal energy resource due to the SLR in this region also being studied [20], and increases in the tidal range resource being simulated with modest (1m) SLR scenarios. A very good review by Haigh et al. [21] discusses that as tidal range schemes are predominately in regions of tidal resonance, the impact of sea-level rise is likely to reduce the resource – although the impact of physical and societal reactions and interactions may have local scales changes to some estuaries. Therefore, identifying estuaries sensitive to changes in the tidal dynamics for the coming century appears important for both flood risk – and tidal energy resource mapping.

IV. DISCUSSION

The 1-D hydrodynamic model, described in Equations 4 and 5, numerically simulates the analytical solution to the three physical processes described in Section 2 (including their interactions): see Figure 2. The 1-D hydrodynamic model was applied to a range of estuary configurations: Estuarine lengths, water depths (constant throughout the domain) and tidal amplitudes at the open boundary were simulated to provide a fast look up table for identifying estuarine features suitable for tidal energy. The maximum tidal amplitude in the entire domain, alongside the peak maximum current simulated, was calculated to generate a quick look-up table to establish likely tidal amplification in an estuary – and therefore determine the likelihood of a potential tidal energy resource. It must be acknowledged that although this simplified approach has many assumptions (e.g. constant bathymetry that will impact funnelling of tidal energy), the simplified estuarine amplification approach illustrates some generic rules that could help mapping the tidal energy resource and likely changes in the coming century. Furthermore, it is hoped the simple relationships demonstrated in Figures 3 and Figure 4 can be combined with the recent NASA Satellite Water and Topography satellite data (SWOT: https://swot.jpl.nasa.gov/ as the data will resolve estuarine dynamics at ~ 50m resolution) to map the global estuary tidal-energy resource and monitor future changes in the tide

Changes in the tide, relative to the boundary condition (i.e. at the mouth or "coast"), were estimated using our 1D model to estimate the likely increase of the tide an estuary could produce (i.e. not the relative change in tide spatially). As water depth effects the amplification if the tidal resource, two examples are given: Figure 3 shows the potential estuarine amplification for shallow estuarine geometries (i.e. water depths ~10m), whilst Figure 4 shows the potential estuarine amplification for deep estuarine geometries (i.e. water depths ~50m).

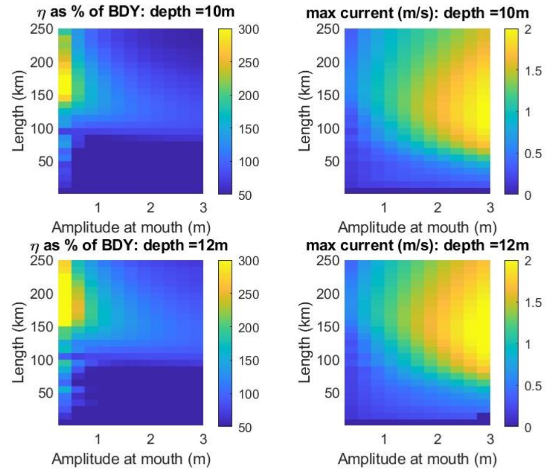

Fig. 3 Numerically simulated impact of tidal amplification , relative to the tide at the estuary mouth (so-called boundary condition called BDY in an idealised estuary of 10m depth (top panels) and including a 2m MSL rise (bottom panels). The relative change to tidal amplification (δM2) shown in left panels and the estimated maximum tidal currents within the estuary on the right hand panels.

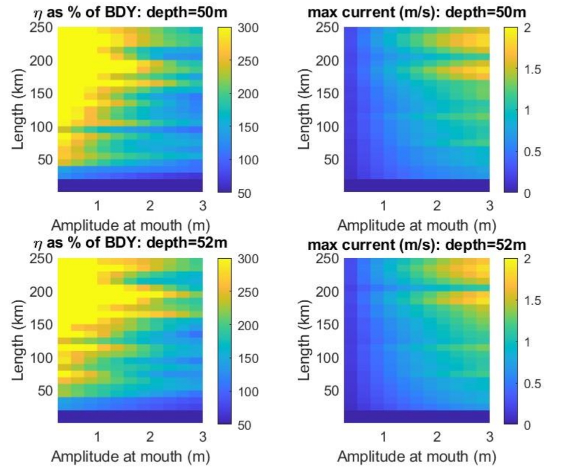

Fig. 4 Numerically simulated impact of tidal amplification , relative to the tide at the estuary mouth (so-called boundary condition called BDY in an idealised estuary of 10m depth (top panels) and including a 2m MSL rise (bottom panels). The relative change to tidal amplification (δM2) shown in left panels and the estimated maximum tidal currents within the estuary on the right hand panels.

Figure 3 demonstrates shallow estuaries likely need to be >150km long and with a tidal amplitude >2m required to amplify the tide sufficiency for an economically viable tidal energy resource (i.e. tidal range >5m) and tidal amplitudes above 2m in estuary lengths of at least 100km, for currents to exceed 2m/s (considered economically viable tidal-stream energy sites). In a deeper estuary system, when a constant depth of 50m is used, viable tidal-range energy sites maybe possible in estuaries of 150km or more (i.e. for deeper estuaries, the tide is amplified greater, due to continuity, and so shorter estuaries can provide tidal energy locations) – however the associated tidal currents are lower. The tidal energy resource was effected by Mean Sea-level rise in both deep (Fig. 4) and shallow (Fig. 3) estuaries (2m added to bathymetry shown in the bottom panels), and differences in the pattern of tidal amplification was found.

V. CONCLUSION

Changes to the tidal range energy resource were found due to mean sea-level rise and estuarine morphology (i.e. bathymetry and coastline shape) – with changes of tidal amplification along an estuary length. Therefore, estuarine tidal energy resource is likely to change within the lifetime of a tidal power plant development (i.e. up to ~100 years) including optimal locations for development. Mean sea-level rise, likely within the lifetime of a tidal power plant, was found to reduce amplification and tidal energy resource. However, potential changes to the tidal amplitude at the estuary mouth (i.e. changes to the shelf sea tide) was found to impact the tidal-energy resource more than mean sea-level rise. The development of a simplified 1-D hydrodynamic model also successfully developed a broad guide to estuarine geometries suitable for exploration of tidal energy: typically, ~150km long estuaries with M2 tidal amplitudes above 1m offshore of the estuary are needed. Future work should aim to validate this approach – especially as our simplified model could not recreate all the changes to tidal dynamics reported in the literature. We therefore recommend the interaction between likely changes to the tide, sea-level rise and coastline management strategies, and any tidal energy power plant, ought to be numerically simulated to resolve the yield, and possible environmental impact assessment, within the lifetime any proposed tidal energy scheme. Furthermore, given proposed changes to tidal dynamics due to anthropogenic influences (port dreading and coast reclamation) and mean sea-level rise, the environmental impacts of proposed schemes could be judged on a future "baseline" rather than current tidal dynamics.

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