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Saltmarsh vegetation alters tidal hydrodynamics of small estuaries

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ABSTRACT

Saltmarshes in most estuaries in the UK and elsewhere are heavily exploited for numerous purposes including farming, fishing, and recreation. In this study, a computational model was used to investigate the impact of saltmarsh vegetation on tidal dynamics and residual currents in three distinctly different estuaries in Wales, UK, in order to understand the impacts of marsh vegetation on wider estuarine hydrodynamics. The three estuaries, Mawddach, Taf and Loughor, vary in size, tidal range, exposure, and saltmarsh coverage. Tidal constituents and residual currents were calculated using a year-long simulation of tidal dynamics. Tidal dynamics are discussed in terms of five important primary tidal constituents (M2, S2, N2, K1, O1) and two shallow water constituents (M4, MS4). The results reveal that saltmarsh vegetation reduces the amplitude of both primary and shallow water tidal constituents not only on and at the proximity of marsh platforms but also in the wider estuary, mostly confined to tidal channels and surrounding intertidal areas. Most notable changes were observed in the middle and upper estuary. Notable changes to residual current velocities were observed on marsh flat areas and in tidal channels and saltmarsh creeks which indicates that changes to marsh vegetation have the potential to alter sediment transport and hence wider estuary hydrodynamics. Our results will be useful when making decisions to restore, reclaim and realign existing saltmarshes for environmental, conservation and socioeconomic purposes, or integrate them in nature-based solutions for estuarine flood and erosion management.

1. Introduction

Saltmarshes are an integral feature of many estuarine systems. They are coastal wetlands which are typically found in the intertidal region of sheltered environments between the marine and terrestrial boundary of estuaries (Fagherrazzi et al., 2012). The terrestrial border of a saltmarsh is defined by the Highest Astronomical Tide elevation (HAT). On the seaside, the marsh edge borders the saltwater body and typically connects with estuarine mud flats (Foster et al., 2013). The vegetated platform between the two borders, which is normally dissected by tidal creeks, exhibits a range of salt-tolerant species including grasses, bushes, and reeds. The lower marsh, typically located between the seaward border and the Mean High Water Neap tidal level (MHWN), is flooded twice daily. The middle marsh, located between MHWN and Mean High Water Sring tidal level (MHWS), is flooded during the spring half of the tidal cycle. The upper marsh is located between MHWS and HAT and floods during storms and very high tides (Foster et al., 2013).

Saltmarshes have been widely recognised as valuable natural capital, providing numerous ecosystem services to coastal communities and environmental benefits including carbon storage, creating habitat space for a wide range of secondary animal and algal species and reducing contaminants (Barbier et al., 2011; Martínez et al., 2007; UNEP 2006). In recent years, the coastal and flood protection services provided by saltmarshes have received increased attention (e.g., Bennett et al., 2020; Fairchild et al., 2021; Leonardi et al., 2018). Saltmarshes are known to attenuate waves and surges, which in turn contribute to flood mitigation (e.g., Jadhav et al., 2013; Losada et al., 2016; Leonardi et al., 2018; Möller, 2006; Möller et al., 2014; van Veelen et al., 2020). As such, they have been integrated with many flood and coastal erosion mitigation interventions developed based on nature-based coastal management concept (e.g., Pontee et al., 2016; Temmerman et al., 2013). These flood mitigation properties arise through the complex interaction between saltmarsh vegetation and flow over the marsh platform, and have been investigated by Dalrymple et al. (1984); Fagherazzi and Furbish (2001); Paul et al. (2016); Pujol et al. (2013); van Veelen et al. (2020, 2021) and many others. Collectively, these studies have found vegetation alters the flow structure on marsh flats. Emerging evidence suggests that the structural properties of marshes - notably plant stiffness, plant physical

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traits, vegetation density (e.g., Losada et al., 2016; Paul et al., 2016; Möller, 2006; Tempest et al., 2015; Västilä and Järvelä, 2014; van Veelen, 2020) and the spatial extent of marshes (Donatelli et al., 2018; Fairchild et al., 2021) - can influence the capacity of marshes to attenuate wave and current energy. For example, it has been observed that the drag coefficient of flexible vegetation can be up to 70% lower than equivalent rigid marsh vegetation depending on the hydrodynamic condition, and therefore can be considerably less effective at dampening wave and current energy (Luhar and Nepf, 2011; van Veelen et al., 2020). Additionally, the potential of saltmarshes in attenuating storm surges has been observed at numerous instances (Fairchild et al., 2021; Hu et al., 2015; Wamsley et al., 2010), although the level of attenuation is strongly context-dependant in terms of marsh location, extent, and the geomorphology of the estuary system. Wamsley et al. (2010) highlights the large influence of context in relation to the overall effect on surge reduction dependant on the landscape and storm strength.

The role of saltmarsh vegetation on local flow and wave attenuation over the marsh platform is well understood. However, the impact of marsh vegetation on the hydrodynamics of the wider estuary is still unknown. Numerical simulation studies by Bennett et al. (2020) and Fairchild et al. (2021), focused on Welsh estuaries, revealed that degradation or loss of saltmarsh vegetation can have widespread impacts on the hydrodynamics of the estuary, both near and far field of the marsh location and have far reaching implications on flooding. Evidence suggests that effects of vegetation may be particularly important in the hydrodynamics of smaller estuaries where saltmarshes cover a significant proportion of the intertidal area, while being far more common than larger estuaries and estuary complexes throughout the world (Emmett et al., 2000; Manning, 2007; Roy et al., 2001).

As well as mitigating flood risk through altering hydrodynamics, saltmarshes also play a direct and vital role in estuary sediment transport by acting as sediment sinks as a result of sediment deposition on the marsh flat via the altered tidal and wave regime. They can also act as sediment sources through the erosion of marsh platform or edge during extreme conditions (Donatelli et al., 2018, 2020). Flood tidal currents carry sediment eroded from tidal flats and other inter- and sub-tidal sedimentary features into saltmarshes in suspension. The drag induced by saltmarsh vegetation slows down tidal currents and allow sediment to fall out of suspension and accrete on marsh platforms, thus acting as a sediment sink. Similarly, sediment carried along the freshwater inflow from upstream river can also be deposited on the marsh platform. The process can reverse during ebb tide. If ebb current velocities are stronger than the flood currents then, the marsh platform has the tendency to erode and become a sediment source to the estuary. On the other hand, strong tidal currents and large waves can erode the marsh edge and supply sediment into the other areas of the estuary (Dyer et al., 2000; Fagherazzi et al., 2012; Leonardi et al., 2016 Pethick, 1992, 1994). As a result, the changes to hydrodynamics due to marsh vegetation, both local and far field, can potentially alter the estuarine sediment transport regime, which may have wider implications on estuarine morphodynamics over a long period of time (Donatelli et al., 2018).

The aim of this paper is to investigate the implications of saltmarsh vegetation on the hydrodynamics of a whole estuary system under different estuarine, hydrodynamic and saltmarsh contexts. We studied three small tide-dominated macro- and meso-tidal estuaries in Wales, United Kingdom (UK) which have distinctly different characteristics, using numerical hydrodynamic modelling. The numerical tidal models of the three estuaries were developed using the Delft3D coastal modelling suite (Lesser et al., 2004). The important tidal constituents and residuals are derived and analysed to describe estuary-wide flow dynamics, focusing on how the estuary size/shape and saltmarsh extent impact the overall estuarine hydrodynamic regime.

2. Study sites

Estuarine hydrodynamics are primarily driven by the tidal and wave penetration into the estuary and the freshwater flow from the river. In most small estuaries in high latitudes, river flow is significantly smaller when compared with the tidal regime. When wave penetration into the estuary is constrained by the size and the orientation of the mouth of the estuary with respect to incoming wave approach direction, hydrodynamics is dominated by the tides. Three small estuaries in Wales, UK, Mawddach, Taf and Loughor estuaries, were selected as case study sites in this research to investigate the impacts of saltmarsh vegetation on wider estuarine hydrodynamics.

Although Loughor is classified as a small estuary, it's surface area is an order of magnitude larger than the other two. All three estuaries are tide-dominated, significantly sheltered from the penetration of incoming waves reaching from the predominant wave approach direction, have small fluvial discharges compared to the tidal prism, and have extensive coverage of saltmarshes when compared to the surface area of the estuary. Their marshes (Fig. 1) have been extensively exploited for land reclamation for farming purposes and animal grazing thus reducing the vegetation cover. On the other hand, they are explicitly different in size, morphology and tidal range, which allows us to distinguish the role of estuarine characteristics on saltmarsh assisted flow modulation.

2.1. Mawddach estuary

Mawddach is a shallow, bar-built, macro-tidal estuary (Fig. 1c). The estuary empties into Cardigan Bay in West Wales (Manning, 2012). The estuary has a spring and neap tidal ranges of 5.8 m and 1.8 m respectively (UK Hydrographic Office). The approximate surface area of the estuary is about 5.22 km^2 at mean sea level. The length of the estuary from the mouth at Fairbourne sand spit to the tidal limit close to Penmaenpool bridge is approximately 10 km. The width of the lower estuary is about 2 km, which narrows down to about 500 m at the mouth by a sand spit. The intertidal area of the estuary contains extensive tidal flats and saltmarshes. The spring tides produce tidal velocities exceeding 1 m/s at the narrow estuary mouth. The mean tidal prism has been estimated as 10.7×10^6 m^3. The primary river systems that feed the estuary are Afon Mawddach and Afon Wnion. The mean freshwater discharge into the estuary is 20 m^3/s, which is approximately 20% of the tidal prism. A narrow tidal channel of less than 4 m deep and surrounded by intertidal mud flats runs along the estuary. 41% of the intertidal estuary area is covered by saltmarshes (NRW, 2015), totalling 200 ha (Fig. 1c) (Ladd, 2018). The lower Mawddach estuary occupies highly dynamic large sand flats which exposes during low tide (NRW, 2015; Robins, 2011).

The natural shape and the dynamics of Mawddach estuary had been significantly constrained by several embankments constructed for land reclamation and management purposes during the 19th century. The longest embankment of about 4 m height runs along the south bank of the estuary from Morfa Mawddach station to Barmouth. Additional embankments have been constructed at Fairbourne, Afon Arthog and several other locations along the north bank, mainly aiming at coastal erosion and flood control purposes (Robins, 2011).

2.2. Taf estuary

Taf is a tide-dominated, funnel-shaped, coastal plain estuary located in Carmarthen and empties into Carmarthen Bay on the South Wales coast (Fig. 1d). The estuary is a part of the Carmarthen Bay Three Rivers confluence and covers a surface area of 9.2 km^2 at MSL. The estuary is classified as macro-tidal with a spring tidal range at the mouth of the estuary of 7.5 m and neap tidal range of 3.7 m. The tidal prism is approximately 17.7 x10^6 m^3 and the tidal estuary extends 15 km upstream from the river mouth at spring tide. Tidal currents exceeding 2.2 m/s have been measured at the mouth of the river. The River Taf feeds freshwater into the estuary. The average freshwater flow into the estuary is around 7.0 m^3/s (Ishak, 1997), which is very small compared to the large tidal prism driven by the macro-tidal regime. Two other small

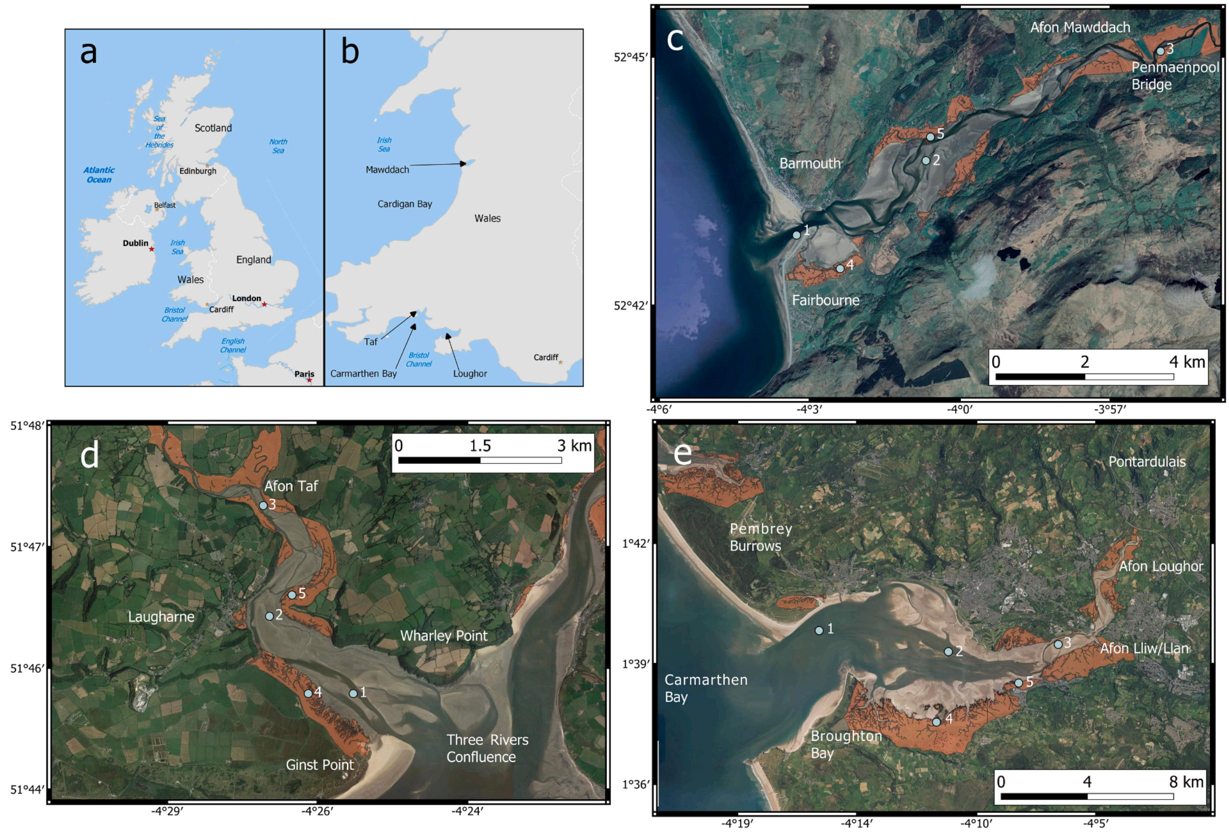

Fig. 1. A map of the UK (**a**); locations of Mawddach, Taf, and Loughor Estuaries in Wales (**b**); Close-up of Mawddach (**c**), Taf (**d**) and Loughor (**e**) estuaries. Saltmarsh coverage of the three estuaries is highlighted in brown.

rivers Cywyn and Coran also discharge into the Taf Estuary. The estuary is very sheltered from the waves approaching from Carmarthen Bay. Locally generated small wind waves dominate the wave field inside the estuary (Bennett et al., 2020; van Veelen, 2020).

The main tidal channel runs along the estuary and branches into two or three small channels upstream. However, the channel position and the surrounding sand flats in the lower and middle estuary rapidly evolve as a result of complex sediment reworking driven by tidal currents. The intertidal areas of Taf Estuary occupy a substantial amount of saltmarsh habit of 299 ha, worth 36.5% of the total intertidal area (Fig. 1d). Saltmarshes spread across the estuary from the mouth to the upper estuary. Numerous interventions in saltmarsh areas including building hard sea defences to reclaim land have taken place in the 17th and 18th centuries. In recent decades Taf has seen a significant increase in marsh areas which has led to the configuration of the estuary found today. Saltmarshes in the estuary are regularly used as animal grazing grounds.

2.3. Loughor estuary

Loughor Estuary, the largest of the three estuaries widely known as Burry Inlet, is located in the northern side of Bristol Channel between Carmarthenshire and Swansea and discharges into Carmarthen Bay (Fig. 1e). It is designated as spit enclosed, funnel-shaped coastal plain estuary (Elliott and Gardiner, 1981). The tidal estuary extends 16 km upstream of Carmarthen Bay at spring tide. The south bank of the estuary runs from Broughton Bay, Gower at the mouth to Pontardulais in the east while the north bank encompasses the coastline from Pembrey Burrows at the mouth east to Pontardulais (Fig. 1e). Two main rivers Loughor and Afon Lliw/Llan enter the estuary. The mean freshwater upstream flow of Loughor is 2.1 m^3/s (National River Flow Archive, 2021). The macrotidal Loughor Estuary has a spring tidal range of 7.1 m and neap tidal range of 3.3 m. The tidal prism of the estuary is 2.4×10^8 m^3 (Robins, 2009). The large tidal range drives tidal currents exceeding 1.7 m/s in certain areas of the estuary. The surface area of the estuary is approximately 45 km^2 at MSL, with an intertidal area excluding saltmarsh of 4.493 km^2 (Bristow and Pile, 2003). Saltmarshes cover 2200 ha (Joint Nature Conservation Committee, 2008). The estuary is strongly flood-dominated. The tidal prism is several orders of magnitude larger than the freshwater discharge into the estuary (Denner et al., 2015; Elliott and Gardiner, 1981; Robins, 2009).

Waves that enter the Loughor estuary from Carmarthen Bay break at the sand bars located at estuary mouth. Waves within the estuary are limited to locally generated wind waves. There is a significant littoral drift into the estuary where net sediment transport is in the south-west direction (Pye and Blott, 2010; Robins, 2009). The large tidal range drives strong tidal currents within the estuary, forming large sand flats and mega ripples. The main tidal channel occupies the central part of the estuary. A well-developed ebb tidal delta exists seaward of the estuary mouth. The area immediately landward of the mouth resembles a flood tidal delta (Denner et al., 2015; Elliott and Gardiner, 1981). 31.6% of the intertidal area of the estuary is covered by saltmarshes (http://lle.gov.wales/catalogue/item/SaltmarshExtents), some of which are used for animal grazing during low tide (Abu-Bakar et al., 2017) (Fig. 1e).

Historic evidence of all three estuaries suggests morphodynamic evolution involving tidal channel migration, evolution of sand bars and spits, and changes to saltmarshes at a number of time scales including rapid changes over a few months to long term changes over decades. A summary of the key features of the three sites is given in Table 1. It can be seen that the surface area of the Loughor is an order of magnitude larger than that of Mawddach. The surface area of the Taf is nearly a twice that of Mawddach. The sinuosity of all three estuaries is very similar, 1.36 in Mawddach, 1.4 in Taf and 1.5 in Lougher. While Mawddach is a mesotidal estuary both Taf and Loughor are macrotidal

Table 1
Key features of Mawddach, Taf, and Loughor estuaries.

Estuary	Estuary type	Surface area (m^2)	Spring tidal range (m)	Tidal prism (m^3)	Saltmarsh coverage as a% of surface area	Primary vegetation type/s
Mawddach	bar-built	5.22 km^2	5.8	10,707,000	38.3	*Ariplex portulacoides, Spartina angica*
Taf	coastal plain	9.20 km^2	7.5	17,700,000	36.5	*Ariplex portulacoides, Spartina angica*
Loughor	Coastal plain	45.0 km^2	7.1	244,879,000	31.6	*Ariplex portulacoides, Spartina angica*

estuaries. Mawddach has the highest percentage of saltmarsh coverage compared to its surface area while Loughor has the smallest. The predominant saltmarsh vegetation type is the same in all three estuaries.

3. Computational modelling and methodology

3.1. Computational modelling

Depth averaged numerical hydrodynamic models for each of the three estuaries were developed using the computational coastal modelling suite Delft3D (Lesser et al., 2004). Delft3D has been extensively used to research a wide range of coastal environments, due to its capability in simulating coastal and estuarine hydrodynamic and morphological behaviour. Recent studies have highlighted the capability of Delft3D to study the interaction of coastal vegetation and hydrodynamics (Bennett et al., 2020; Best et al., 2018; Hu et al., 2015, 2018). The depth averaged hydrodynamic model, which calculates unsteady flow resulting from tidal and meteorological forcing was used in this study. The model governing equations are given below.

Where the depth-averaged continuity equation is given by Eq. (1):

$$\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)U\sqrt{G_{\eta\eta}}\right]}{\partial \xi} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)V\sqrt{G_{\xi\xi}}\right]}{\partial \eta} = (d+\zeta)Q \tag{1}$$

Where U and V are the depth-averaged velocities, and Q represents the contributions per unit area due to the discharge or withdrawal of water, precipitation and evaporation. The momentum equations in ξ- and η-directions are given by Eqs. (2) and 3 respectively.

$$\frac{\partial U}{\partial t} + \frac{U}{\sqrt{G_{\xi\xi}}}\frac{\partial U}{\partial \xi} + \frac{V}{\sqrt{G_{\eta\eta}}}\frac{\partial U}{\partial \eta} + \frac{UV}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \xi} - \frac{V^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi} - fV = -\frac{1}{\rho_0\sqrt{G_{\xi\xi}}}P_\xi - \frac{gU\sqrt{U^2+V^2}}{C_{2D}^2(d+\zeta)} + F_\xi + F_{s\xi} + M_\xi \tag{2}$$

$$\frac{\partial V}{\partial t} + \frac{U}{\sqrt{G_{\xi\xi}}}\frac{\partial V}{\partial \xi} + \frac{V}{\sqrt{G_{\eta\eta}}}\frac{\partial V}{\partial \eta} + \frac{UV}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi} - \frac{U^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \xi} + fU = -\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta - \frac{gV\sqrt{U^2+V^2}}{C_{2D}^2(d+\zeta)} + F_\eta + F_{s\eta} + M_\eta \tag{3}$$

Where P_ξ and P_η are the pressure gradients, F_ξ and F_η represent the unbalance of horizontal Reynold's stresses, and M_ξ and M_η represent the contributions due to external sources or sinks (e.g. hydraulic structures, discharge or withdrawal of water, or the impact of vegetation on flow).

The numerical model domains of the three estuaries, shown in Fig. 2, used orthogonal structured grids to provide increased resolution in areas where flow pattern can be particularly variable. The grid resolution refines from coarser resolution offshore to approximately 30 m x 30 m within the estuary. Bathymetric data for each estuary is assembled from a combination of available LiDAR data, UK Hydrographic Office (UKHO) data, and measurements taken as part of the CoastWEB project funded by the UK Natural Environment Research Council (https://www.pml.ac.

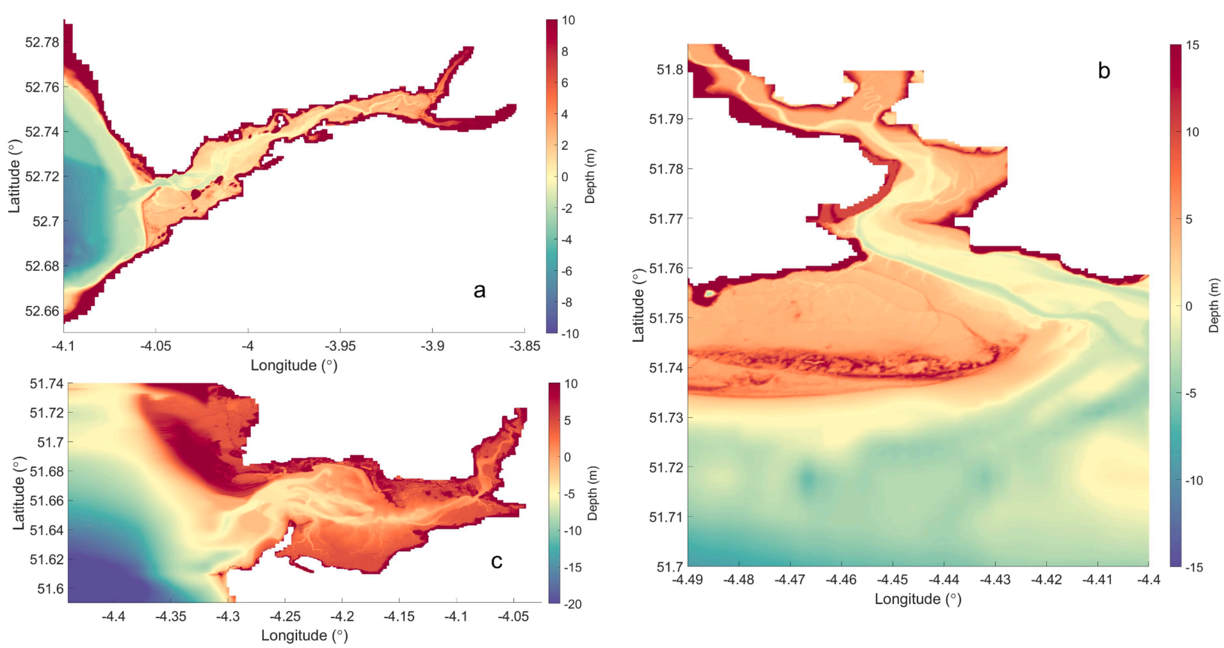

Fig. 2. Numerical model domains and seabed bathymetries of (**a**) Mawddach, (**b**) Taf and (**c**) Loughor estuaries respectively. The domains include estuaries up to the upstream tidal limit. The offshore boundaries extend offshore to sufficient depths where tidal boundary conditions can be implemented from a global tide model.

uk/CoastWeb/Home). The mean river flow for each estuary provided in Section 2 was used to provide river input within each model. It is noted however that compared to the tidal prism in each of the three estuaries, river input is significantly smaller. The models are driven by time varying tidal conditions specified along open coast boundaries of the model domains. Thirteen tidal harmonic constituents were used to generate the offshore tidal boundary (M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM, M4, MS4, M4).

The models used in this study have previously been validated through a comparison with numerous tidal elevation observations in each estuary. Validation data for the estuaries was supplied by a combination of data provided by Natural Resources Wales, British Oceanographic Data Centre (BODC) tide gauges, and HOBO depth logger water level measurements caried out during the CoastWEB project. Model performance was assessed through the use of regression coefficient R^2 and Root Mean Square Error (RMSE) between measured and simulated tidal elevations. R^2 and RMSE for all three estuaries show that the simulations are in very good agreement with measured data (Table 2). It should be noted that tidal current observations were not available for model validation. In-depth details of model validation are given in the supplementary data to Fairchild et al. (2021) (available online at http://doi.org/10.1088/1748–9326/ac0c45).

Saltmarsh footprints were incorporated into the model domains using marsh shapefiles provided by Natural Resources Wales (http://lle.gov.wales/catalogue/item/SaltmarshExtents). To provide representative vegetation properties across saltmarsh areas, Community Weighted Means (CWM) of plant data provided by the CoastWEB project were utilised following Bennett et al. (2020); Fairchild et al. (2021); and van Veelen et al. (2020). Vegetation parameters used in the models, plant density of 2275 stems/m^2; mean vegetation height of 0.33 m; mean stem thickness at the base of 3.3 mm; mean stem thickness at the tip of 1.8 mm; and plant drag coefficient of 1.0, which were derived by field surveys (Fairchild et al., 2021), were defined based on the representative vegetation type (*Atriplex Portulacoides)*. Plants were considered as single stem rigid cylinders (Dalrymple et al., 1984). The frictional resistance induced by vegetation on the flow field is calculated by Eq. (4) and is incorporated as a sink term in the momentum equation of the numerical model.

$$\overrightarrow{F}(z) = \frac{1}{2}\rho C_D \phi_v(z) n_v(z) |u(z)| \overrightarrow{u}(z) \tag{4}$$

where F is the drag force produced by vegetation per unit volume in N/m^3, ρ is seawater density of 1025 in kg/m^3, $u(z)$ is the horizontal flow velocity profile in m/s, $\phi_v(z)$ is the plant width as a function of height and $n_v(z)$ is the plant density as a function of height (number of stems/m^2) and C_D is a dimensionless drag coefficient.

The open model boundaries were forced using tidal constituents obtained from TPXO8.0 OSU Tidal Inversion Software (Egbert and Erofeeva, 2002) to calculate water surface elevations. Each estuary was modelled both with and without the vegetation cover on marsh platforms to simulate the influence of saltmarsh vegetation on estuarine hydrodynamics. Tidal simulations were carried out over a period of one year between 1st January 2019 and 1st January 2020 in order to encompass a greater number of tidal harmonics accurately. The model time step to ensure model stability was set at 0.1 min for the Loughor model, and 0.2 min for the Taf and Mawddach models. A total of six model runs were simulated, two for each estuary, with and without saltmarsh vegetation, each simulation providing time and space-varying tidal depths and velocities at each grid point in the model domains. The simulation with marsh vegetation replicates the current state of the estuary while that without vegetation is taken as the reference condition to which the impact of the presence of marshes are evaluated.

Table 2
R^2 and RMSE between measured and simulated tidal elevations at the three case study estuaries (Fairchild et al., 2021).

Estuary (location)	R^2	RMSE (m)
Loughor (Burry Port)	0.974	0.272
Loughor (Llanelli docks)	0.954	0.295
Taf (Laugharne South)	0.789	0.163
Taf (Laugharne North)	0.998	0.069
Mawddach (Barmouth RW Bridge)	0.978	0.234

3.2. Tidal harmonics and residuals

Although tides in the open ocean may be largely symmetric and sinusoidal, tidal oscillation in estuaries can be impacted by the size, shape, morphological characteristics, and shallow water depths of the estuary. Tides can be distorted and non-linear, specifically in small estuaries with narrow inlets, by complex morphodynamics and irregular flow damping characteristics (Parker, 1991; Redfield, 1950). Tidal distortions generate phase anomalies between tidal currents and water level fluctuations and generate shallow water harmonics which have frequencies that are multiples of the primary astronomical tidal constituents and, harmonics generated through the interaction between two primary constituents. Shallow water harmonics in general have smaller amplitudes when comparted to primary tidal constituents although some of them can be significant. Most significant shallow water harmonics are M4 that has a frequency twice that of the largest lunar constituent M2; and MS4 which is a compound of M2 and the largest solar constituent S2 (Aubrey and Speer, 1985; Friedrichs and Aubrey, 1988).

A consequence of tidal distortion is the asymmetric tidal oscillations in shallow water (Reeve et al., 2022). This can be explained by the quasi-oscillatory nature of tidal flow orbits driven by the distorted tide. Tidal asymmetry can lead to the generation of residual tidal currents which in turn lead to transport of sediment in the direction of residual currents and morphological changes (De Swart and Zimmerman, 2009; Guo et al., 2016; McCave, 1970). In this study, tidal residuals in the estuaries are calculated by time averaging instantaneous tidal currents at each time step and at each grid point in the numerical model domain. Time averaging is done over the entire simulation period of 1 year (Nihoul and Ronday, 1975; Horrillo-Caraballo et al., 2021). Wetting and drying during a tidal cycle was considered when time averaging tidal currents on marsh beds to determine residual currents.

4. Results

A detailed analysis of tidal dynamics of the three estuaries are presented and discussed in this section, focusing particularly on the important shallow water tidal constituents and the residual currents. Peak flood and ebb tidal currents were also evaluated. The influence of saltmarshes on tidal dynamics is investigated by comparing shallow water tidal constituents and residuals with and without marsh vegetation. Models were run for each of the three estuaries both under the existing estuary configuration (considering all saltmarshes in the estuaries are fully vegetated), and a scenario where vegetation is removed from marsh platforms. The difference between numerous tidal constituents and residual currents with and without marsh vegetation are compared. For example, for a variable $N(x,y,t)$, the difference = [$N(x,y,t)_{\text{with vegetation}}$ - $N(x,y,t)_{\text{without vegetation}}$]. Therefore, negative values in the difference of a particular variable indicates an increase in that variable because of the removal of vegetation from saltmarshes.

4.1. Tidal dynamics

Fig. 3 (left) shows spring neap cycles at the points 1 to 5 in Mawddhach estuary (Fig. 1c). Through the lower and mid estuary in points 1 and 2 (Fig. 3a & b), peak spring tidal water levels exceed 2 m, and are as high as 2.8 m, While the lowest neap tides the tidal water levels peak at approximately 1.5 m. Through the upper estuary and on the two marsh locations (Fig. 1c points 3, 4, & 5) displayed in Fig. 3c, d, & e, most neap

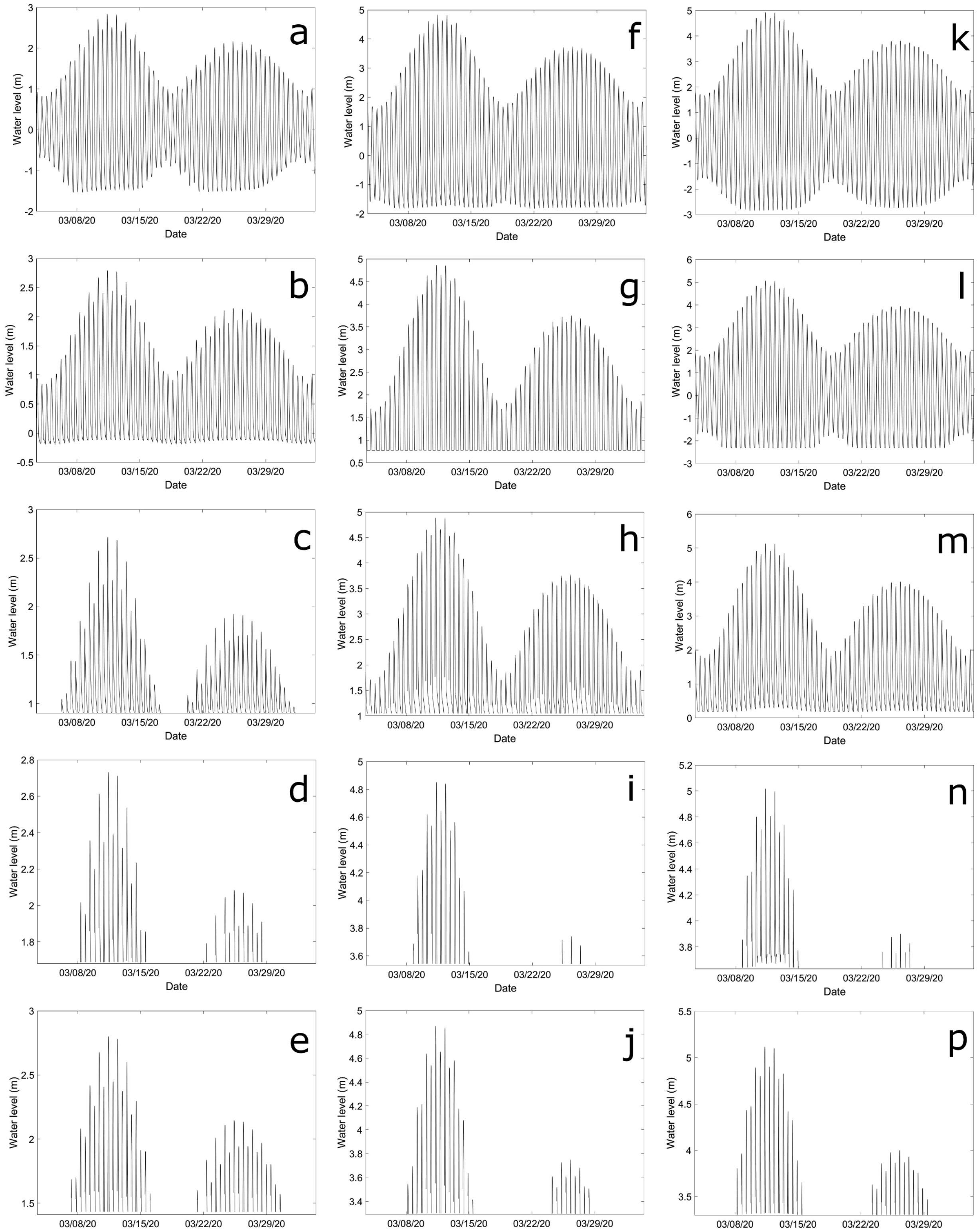

Fig. 3. Sample spring-neap cycles at different locations in Mawddach (left), Taf (middle) and Laughor (right) Estuaries. Subfigures a, b, c, d, & e, display tidal curves for points 1–5 in Mawdddach (Fig. 1c) respectively; subfigures f, g, h, i, & j, display tidal curves for points 1–5 in Taf (Fig. 1d) respectively; and subfigures k, l, m, n, & p , display tidal curves for points 1–5 in Loughor (Fig. 1e) respectively.

tides do not inundate these locations. During spring tides peak water depths in the upper estuary vary between 0.75 - 1.5 m, and 0.4 - 1.2 m on the two marsh locations highlighted.

In the Taf Estuary [Fig. 3 (middle)], spring tide water levels regularly exceed 3.5 m through the upper, middle and lower sections (Fig. 3f, g & h. Locations shown in Fig. 1d), and are over 4.5 m during the highest spring tides. However, for neap tides the water levels do not exceed 3 m. For the two marsh locations shown in Fig. 3i & j (locations 4 & 5 in Fig. 1d), the marshes are not inundated during neap tides. For the highest spring tides water depths at these two points can reach 1.2 m, however during lower spring tides the water depths are much less.

Loughor is the largest estuary with the smallest coverage of marshes of the three estuaries considered in this study. With its close proximity to the Taf estuary and Carmarthen Bay, the tidal profiles for the Loughor [Fig. 3 (right)] show similar characteristics to those shown in Taf. With its large open funnel shape spring tides through the lower to upper estuary (Fig. 1e, points 1–3) have peak water levels between 4–5 m (Fig. 3k, l & m). Neap tides through the estuary do not exceed 3 m. Similar to the Taf Estuary the points on the marshes (Fig. 3n and p) are only inundated during the higher spring tides with maximum depths more than 1.2 m.

Snapshots of peak flood and ebb currents of the three estuaries are shown in Fig. 4. In Mawddach estuary, the tidal flow is constrained by the narrow inlet of the estuary. In the area of the constrained inlet, peak flood and ebb currents reach 1.0 m/s, and 0.6 m/s respectively (Fig. 4a & b). Through the constrained tidal channel in the mid to upper estuary flood currents exceed 0.6 m/s while ebb currents reach 0.4–0.45 m/s. Current velocities in marsh areas are consistently lower than 0.1 m/s during both flood and ebb flow. Through the main body of the estuary peak flood currents are higher than ebb, in the range 0.3–0.4 m/s for the flood tide compared to 0.2–0.3 m/s for the ebb.

Peak tidal currents in the Taf estuary are concentrated within the two main tidal channels (Fig. 4c & d). Overall, the peak flood velocities (Fig. 9a) are higher than the peak ebb (Fig. 4d). Peak flood velocities in the southern tidal channels vary between 0.6–0.8 m/s, while they are slightly lower between 0.4–0.6 m/s in the northern channel. For both channels the highest velocities are confined to the areas near the mouth of the estuary where it flows in to the three rivers confluence. The peak ebb velocities are 0.6–0.7 m/s in both channels near the estuary mouth, reducing to 0.3 m/s through the northern channel towards the middle estuary. In the southern channel ebb velocities remain greater than 0.45 m/s throughout the lower to mid estuary beyond Laugharne. Current velocities on saltmarsh platforms were smaller than 0.075 m/s.

Loughor estuary is characterised by two tidal channels near the mouth of the estuary. Both the flood (Fig. 4e) and ebb (Fig. 4f) currents near the estuary mouth exceed 0.7 m/s in both channels, with the peak

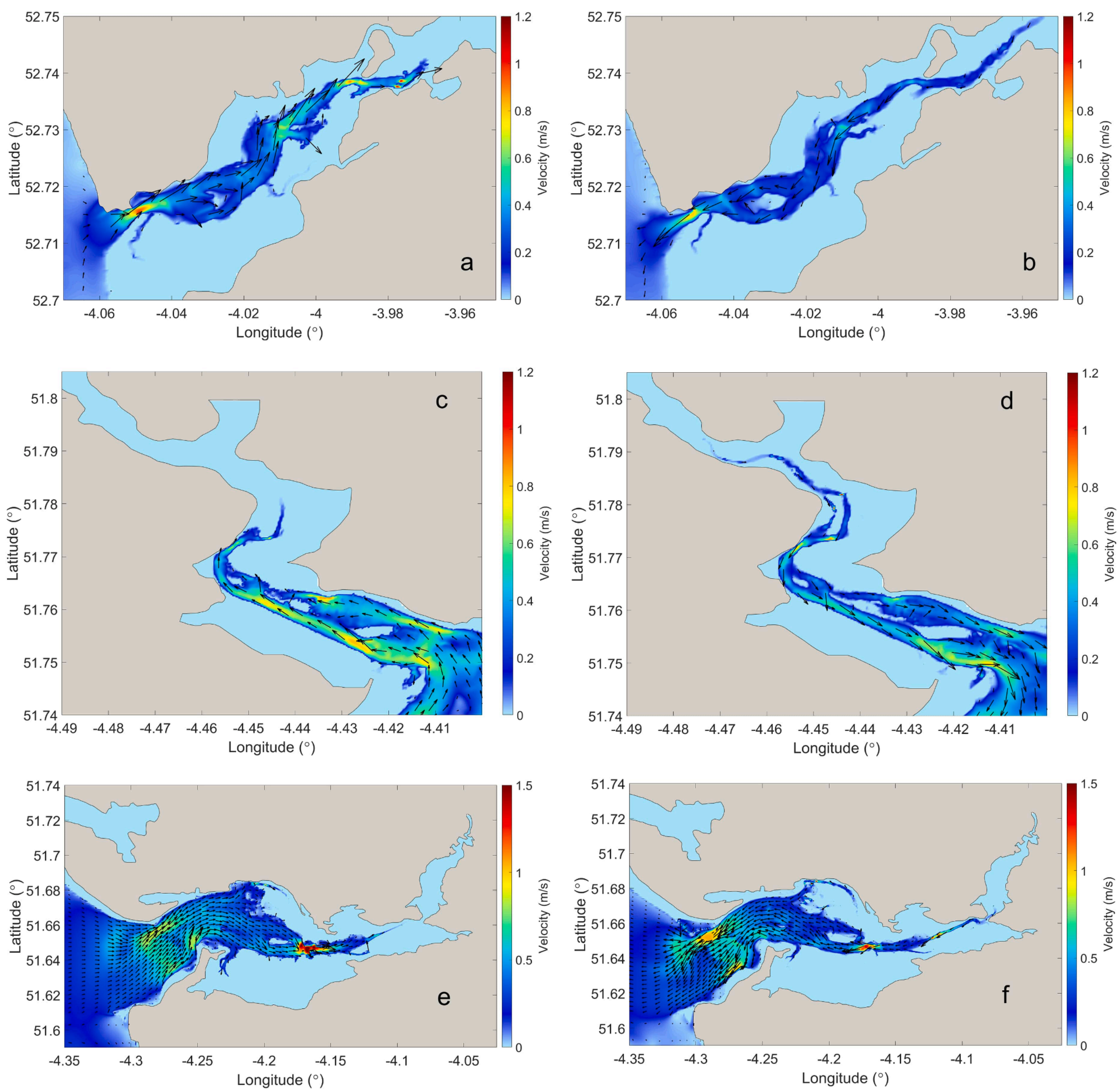

Fig. 4. A snapshot of peak flood and ebb current comparison for the Mawddach [a - peak flood current (16th Jun 2020 04:00), b - peak ebb current (15th June 2020 18:00)]; Taf [(c -peak flood current (16th June 2020 00:00), d -peak ebb current (15th June 18:00)]; and Loughor [(e - peak flood current (15th June 2020 12:00). f -peak ebb current (15th June 12:00)] Estuaries. Vectors indicate direction.

flood current over 1.2 m/s and ebb current over 1 m/s in parts of the channels. Beyond the estuary mouth currents are gradually decreased (< 0.3 - 0.5 m/s). However, as the estuary becomes constrained between the middle and upper estuary, both flood and ebb currents reach a peak of approximately 1.5 m/s. Currents on marsh platforms were less than 0.1 m/s.

4.2. Tidal harmonics

Harmonic analysis of the time histories of tidal variation simulated over a period of one year was carried out to examine the contribution of each tidal constituents to overall tidal dynamics of the three estuaries.

The results reveal that M2 tide is the most significant constituent which primarily governs tidal dynamics of the Mawddach estuary. S2, N2, K1, O1, M4 and MS4 constituents also have a notable contribution

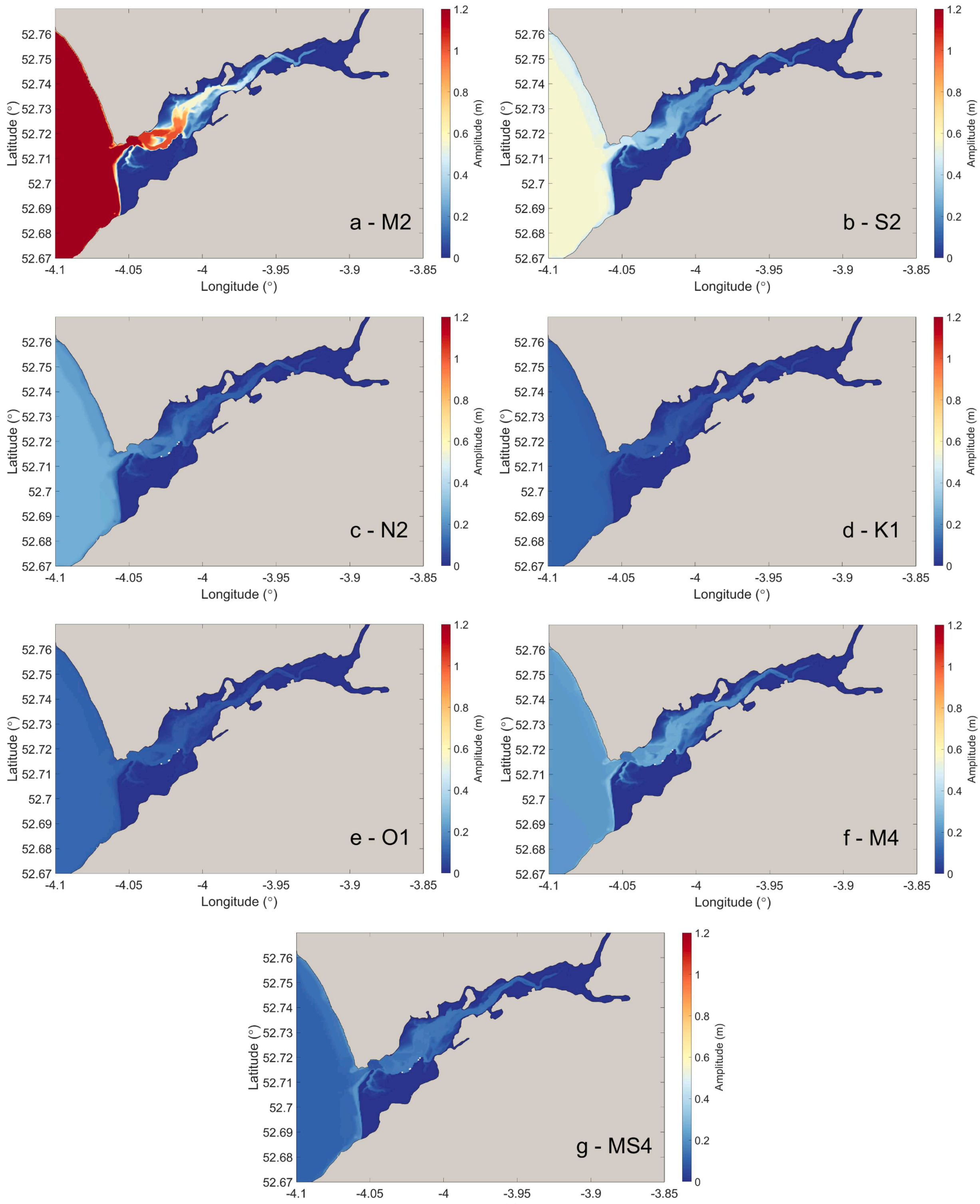

Fig. 5. Amplitudes of the important tidal constituents in Mawddach estuary. **a** - M2, **b** - S2, **c** - N2, **d** - K1, **e** - O1, **f** - M4, **g** - MS4.

(Fig. 5). The constrained mouth of the estuary limits the amplitude of the M2 (Fig. 5a) constituent within the middle and upper estuary, although amplitudes as high as 1.2 m were found around the mouth and at the lower estuary. M2 amplitude rapidly reduced through the middle estuary to the upper estuary although over some marshes located in the middle estuary it is as high as 0.5–0.6 m. The other constituents display similar behaviour, although they have smaller amplitudes than M2. S2 is the second most significant with highest amplitude of 0.6 m in the mouth and lower estuary, and 0.4 m in the middle estuary (Fig. 5b). N2, O1, and K1 (Fig. 5c, d, e) have highest amplitudes of 0.3 m for N2 and 0.2 m for O1 and K1 in the lower estuary. For all three constituents the amplitude reduces to between 0.1 m - 0.2 m in the middle to upper estuary. For the shallow water constituent M4 an amplitude of approximately 0.4 m is maintained from the lower estuary through the middle and decreases only in the upper estuary. MS4 however has a lower amplitude, with 0.25 m consistently through the lower and middle

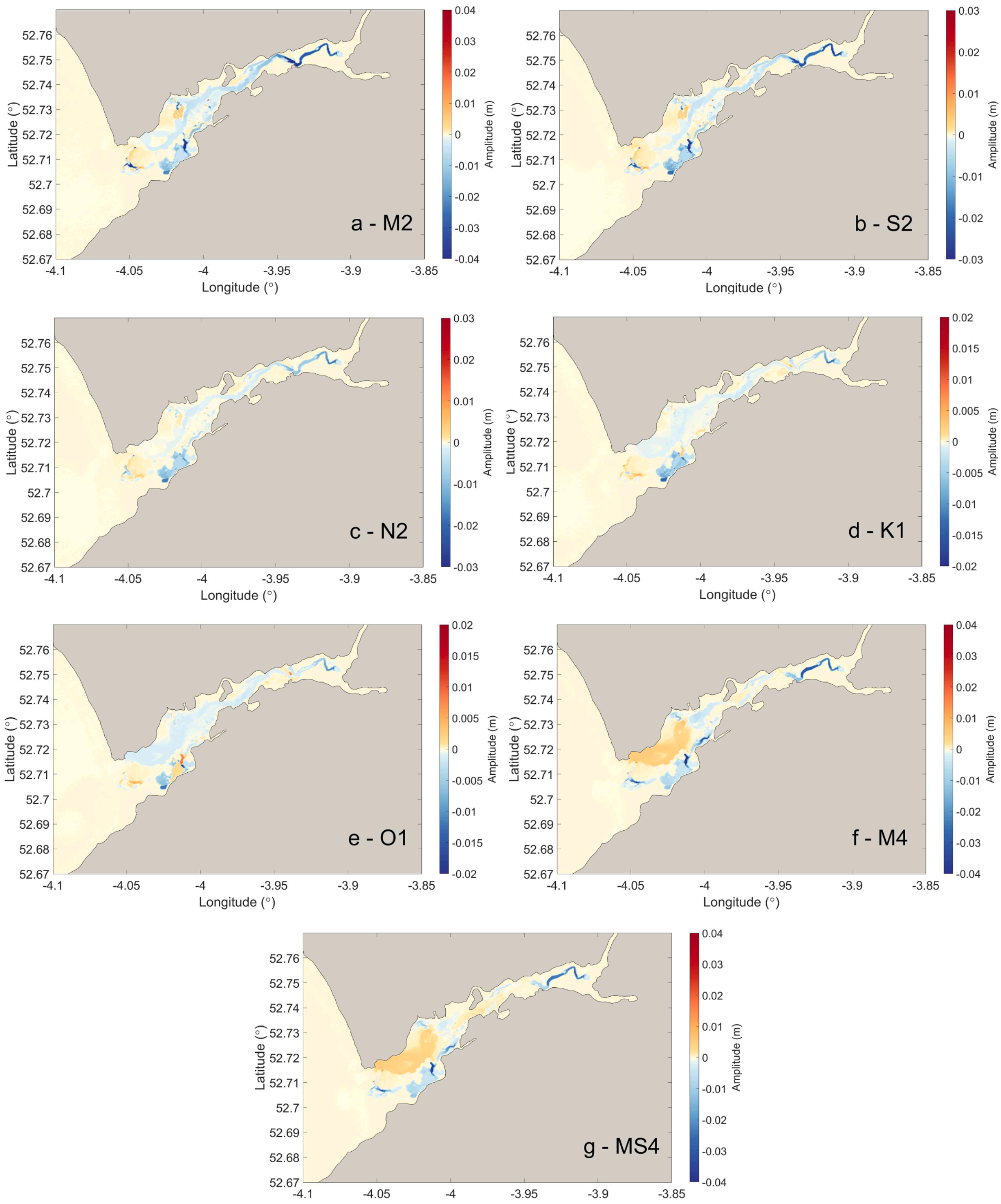

Fig. 6. Difference between tidal amplitudes with and without saltmarsh vegetation for tidal constituents M2, S2, N2, K1, O1, M4 and MS4 in the Mawddach Estuary. **a** - M2, **b** - S2, **c** - N2, **d** - K1, **e** - O1, **f** - M4, **g** - MS4.

estuary, decreasing to 0.1 m in the upper estuary. These reductions in constituents between the mouth and upper estuary are expected due to bottom friction and nonlinear transfer of energy as the tidal wave propagates through the system (Aubrey and Speer, 1985).

The seven most important tidal constituents in Mawddach estuary with and without saltmarsh vegetation are examined in Fig. 6 to understand the influence of marsh vegetation on those constituents. The difference of M2 amplitude with and without vegetation shows that while there are some small increases, the presence of marsh vegetation generally decreases the amplitude of M2 throughout most of the estuary.

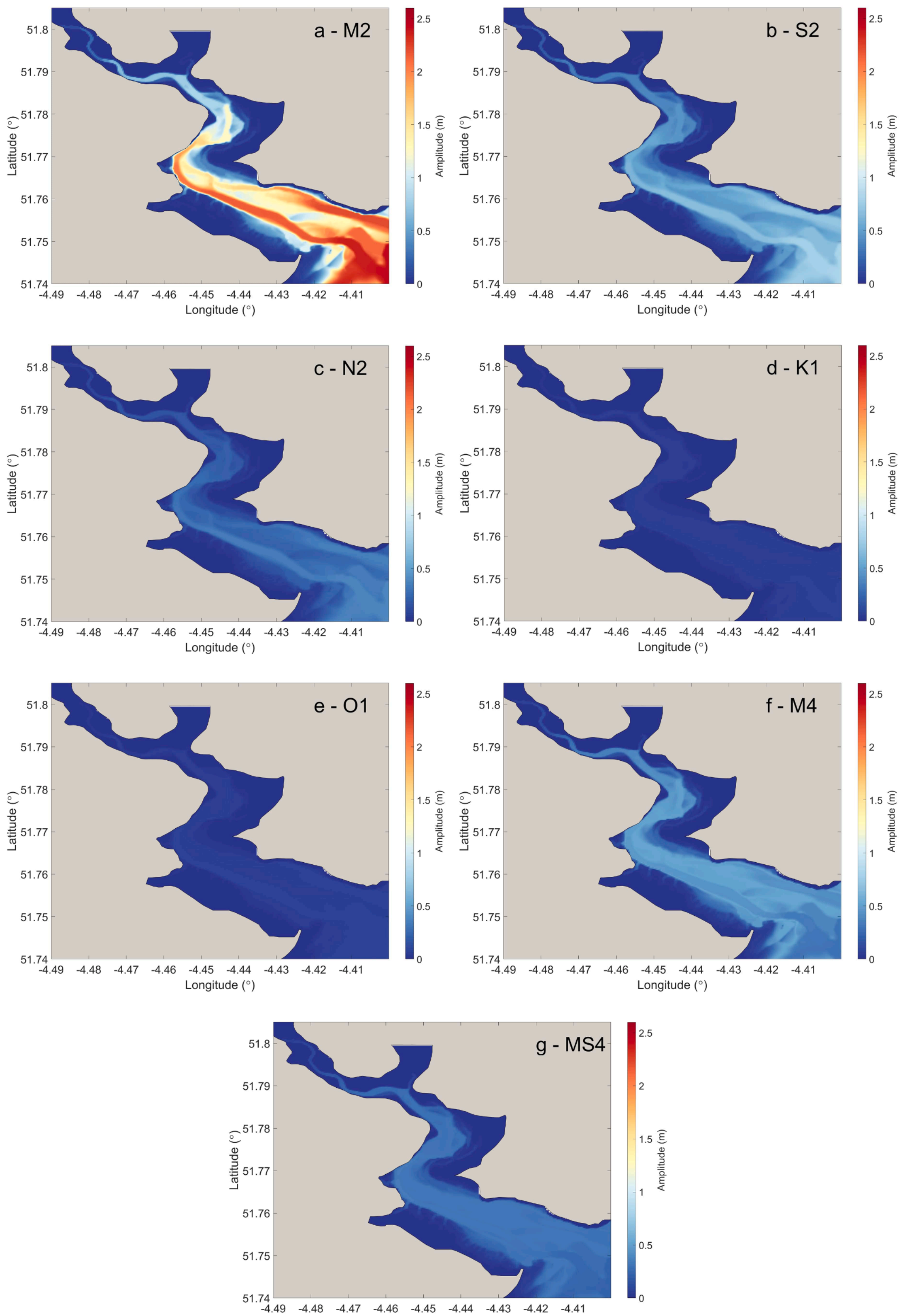

Fig. 7. Amplitudes of the important tidal constituents in Taf Estuary. **a** - M2, **b** - S2, **c** - N2, **d** - K1, **e** - O1, **f** - M4, **g** - MS4.

Although the change in amplitude of the M2 constituent due to the presence of marshes is relatively small (5–10%), the changes are widespread. The greatest reduction in M2 is seen at the upper-middle and the upper estuary, as well as in the tidal channel, except in a very localised area adjacent to the south bank of the lower estuary. This may be due to the fact that most marshes in this estuary are concentrated toward the upper estuary thus reducing the tidal flow due to vegetation-induced friction drag. The S2, N2, K1 and O1 constituents display similar behaviour to that shown by M2. While S2 has similar amplitude differences to M2, the difference in others, N2, K1 and O1, are smaller in amplitude throughout the estuary. The marsh influence on shallow water constituents M4 and MS4 is mixed and complex where their magnitudes are reduced in the upper estuary while amplified in the lower and middle estuaries (Fig. 6f & g). It is clear that the impact of vegetation on tidal dynamics will not be restricted only to the areas covered with saltmarshes.

In Fig. 7 the amplitudes of the main tidal constituents in the Taf estuary are given. Similar to the Mawddach estuary, M2 is the largest tidal constituent in the Taf estuary. The M2 amplitude is greater than 2.5 m at the estuary mouth (Fig. 7a). Amplitudes as high as 2.0 m are observed in the tidal channel in the middle estuary near Laugharne, although it is smaller than 1 m in the upper estuary. The second largest constituent is the S2 (Fig. 7b), with a gradual reduction from amplitudes exceeding 1 m in the mouth of the estuary and estuarine channels, to 0.5 m in the upper estuary. N2 (Fig. 7c) displays a similar pattern to S2 and M2, with maximum amplitudes between 0.5–0.6 m, decreasing to 0. 3 m. Compared with the M2 constituent, the K1 and O1 constituents (Fig. 7d & e) are significantly smaller, with amplitudes less than 0.2 m. The shallow water constituent M4 (Fig. 7f) has the third largest amplitude of the constituents displayed in Fig. 7. The amplitudes are largest through the lower and middle estuary outside of the channels at 0.8 m. This reduces into the upper estuary, as well as in the main channels out into the mouth of the estuary. The MS4 constituent (Fig. 7g) displays a similar pattern to M4 (Fig. 7f), although smaller in amplitude with a maximum of 0.5 m.

The difference of tidal amplitude of the constituents M2, S2, N2, K1, O1, M4, and MS4 in the Taf estuary, with and without saltmarsh vegetation is shown in Fig. 8. Marsh vegetation contributes to consistently reduce the M2 and S2 amplitudes in the tidal channels, on marsh flats and some intertidal areas except in a few localised areas in the middle estuary. The largest reduction of M2 and S2 amplitudes, observed in the tidal channel in the middle and the upper estuary is around 5–15% (Fig. 8a, b). The effect of vegetation on other primary tidal constituents are complex and varied although the largest changes are seen in the middle and upper estuary. This may be attributed to the significant presence of marshes in all areas of the estuary. When the marsh vegetation is removed, the tendency of more water flowing into marsh areas is higher, thus reducing tidal amplitude in channels. The impact on N2 amplitude (Fig. 8c) in the upper and middle estuary is like that of M2 and S2; a very small increase is found in the lower estuary. K1 and O1 amplitudes (Fig. 8d and e) are larger when the marsh is covered with vegetation except in a very few localised areas. However, it should be noted that the amplitudes of K1 and O1 are significantly smaller than that of M2, S2. The impact of vegetation on the two shallow water constituents M4 and MS4 (Fig. 8f and g) is very similar to that on M2 and O2 which indicates the fact that the potential growth of shallow water constituents when propagating upstream of the estuary is compensated by the influence of vegetation. Overall, the reduction of tidal constituents as a result of saltmarsh vegetation cover is widespread and varied across the estuary and the largest changes are found in the middle and upper estuary.

Fig. 9 shows the amplitude of seven tidal constituents M2, S2, N2, K1, O1, M4 and MS4 in Loughor. M2 has the largest amplitude, with values exceeding 2.0 m at most intertidal areas surrounding the tidal channel while it exceeds 2.5 m in the lower estuary which is very close to M2 amplitude outside the estuary inlet. The amplitude is uniformly spread across most of the intertidal areas of the lower estuary. The amplitudes quickly reduce beyond the middle estuary where they are smaller than 1.0 m in the upper estuary. S2 and N2 constituents are comparatively smaller, their amplitude reaching 1.0 m at most intertidal areas. K1 and O1 constituents are considerably smaller than M2, S2 and N2. The amplitudes of these tidal constituents gradually decrease towards the upper estuary. The spatial distribution of M2, S2, N2, K1 and O1 are similar (Fig. 9b–e). The amplitude and spatial distribution of the shallow water constituent M4 within the estuary are comparable to N2. The amplitude of MS4 is slightly smaller than M4 (Fig. 9f & g).

The difference in tidal amplitude between vegetated and non-vegetated saltmarsh scenarios for the seven tidal constituents in the Loughor estuary is presented in Fig. 10. Saltmarsh vegetation in the Loughor causes widespread reduction in M2, S2 and N2 constituent amplitudes (Fig. 10a, b, c) although the change is smaller compared to the other two estuaries. Although the changes are larger within creeks. Changes to K1 and O1 amplitudes are almost insignificant except in a few localised areas (Fig. 10d, e). The two shallow water constituents M4 and MS4 show a reduction because of the presence of vegetation, especially in the middle and upper estuary as well as on marsh platforms and in areas surrounding marshes in the lower estuary. Marsh vegetation has similar effects on both primary and shallow water constituents although the gradual increase in shallow water constituents towards the upper estuary is offset by damping due to vegetation.

The results reveal that although all three estuaries have similar percentages of saltmarsh coverage when compared to the overall surface area of the estuary, the presence of marsh vegetation has a greater impact on the tidal dynamics of smaller estuaries. Irrespective of the size of the estuary, vegetation effects are greater in the vicinity of the marshes although they are not limited to marsh areas.

4.3. Tidal residuals

The tidal residuals, calculated as model grid point averages of the instantaneous current velocities at each time step over the one-year simulation period, taking into account the wetting and drying of marsh platforms at the three sites are compared and contrasted in this section.

Fig. 11 shows residual tidal currents in the current state of each estuary and compares them with no vegetation scenario. For the Mawddach estuary, the tidal flow into the upper estuary via the main channel is constrained by the saltmarsh areas in the mid estuary (Fig. 11a). Residual currents are highest at the inlet of the estuary with velocities in the range 0.35–0.4 m/s. Residual current velocities in the main channel through to the middle estuary are in the range 0.15–0.25 m/s. They gradually decrease through the upper estuary to values smaller than 0.1 m/s. The difference between residual currents with and without saltmarsh vegetation in Fig. 11b shows change in residual velocity in the main channel increases as a result of the presence of marsh vegetation where the maximum increase in residual current is about 40% at certain locations. The largest increases are seen in the channel and the intertidal areas adjacent to the marshes in the middle and upper estuaries. This can be attributed to flow funnelling into the channel in the presence of marsh vegetation. A slight decrease of residual currents can be seen in the intertidal areas surrounding the main channel in areas where marshes are sparse, which can be a result of the increase of tidal asymmetry in marsh areas as a result of vegetation-induced drag on the flow on marsh flats (Blanton et al., 2002). Residual currents are strongly tied with sediment transport regime. The amplification of residual currents in the channel may lead to stronger sediment transport along the channel while reduction of the currents in the surrounding areas may encourage sediment deposition in the intertidal flats. Continuation of this process over a long period of time has the potential to influence channel migration and saltmarsh growth (Karunarathna and Reeve., 2008).

Spatial distribution of residual currents in the Taf Estuary in the

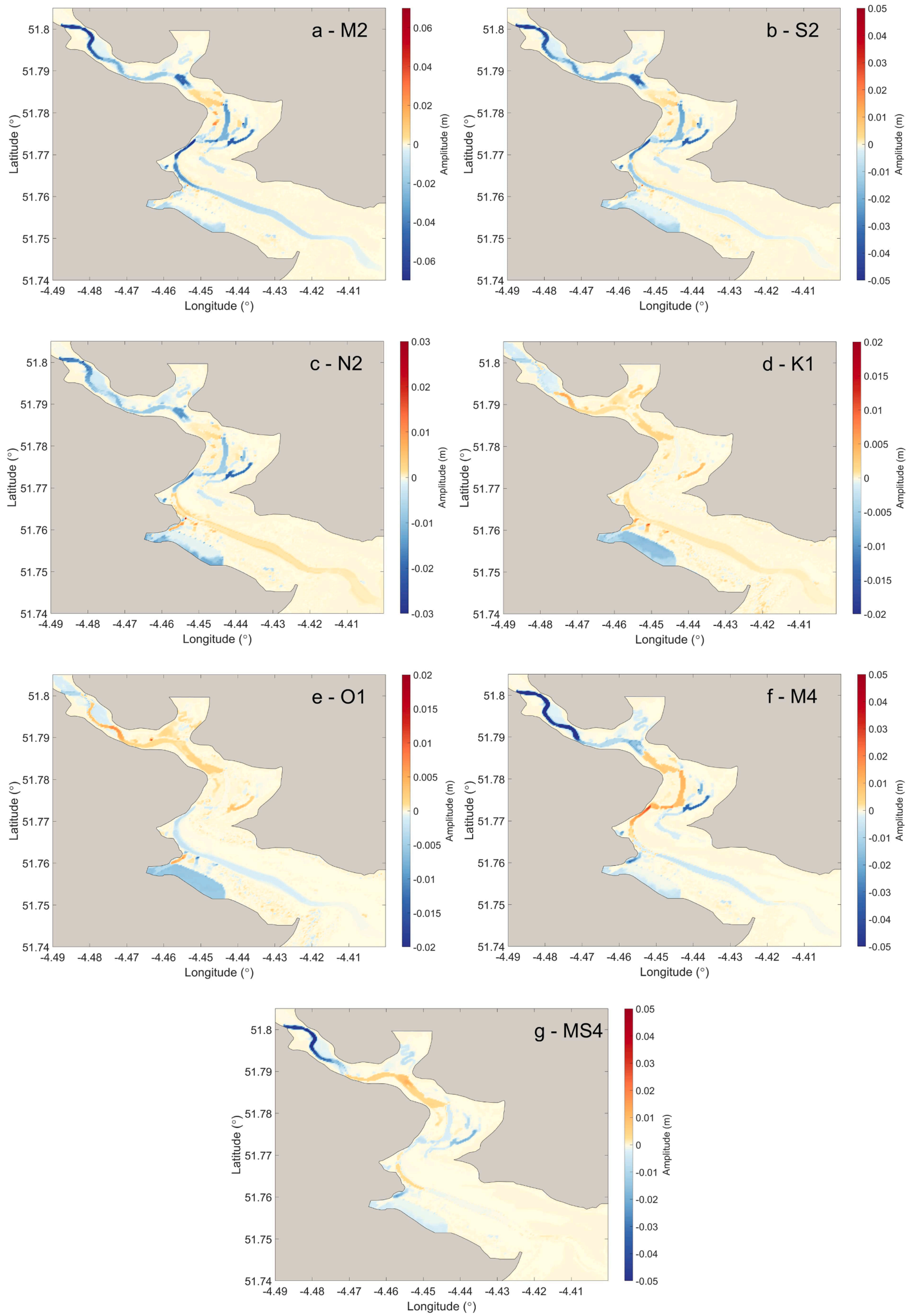

Fig. 8. Difference between tidal amplitudes with and without saltmarsh vegetation for tidal constituents M2, S2, N2, K1, O1, M4 and MS4 in the Taf Estuary. **a** - M2, **b** - S2, **c** - N2, **d** - K1, **e** - O1, **f** - M4, **g** - MS4.

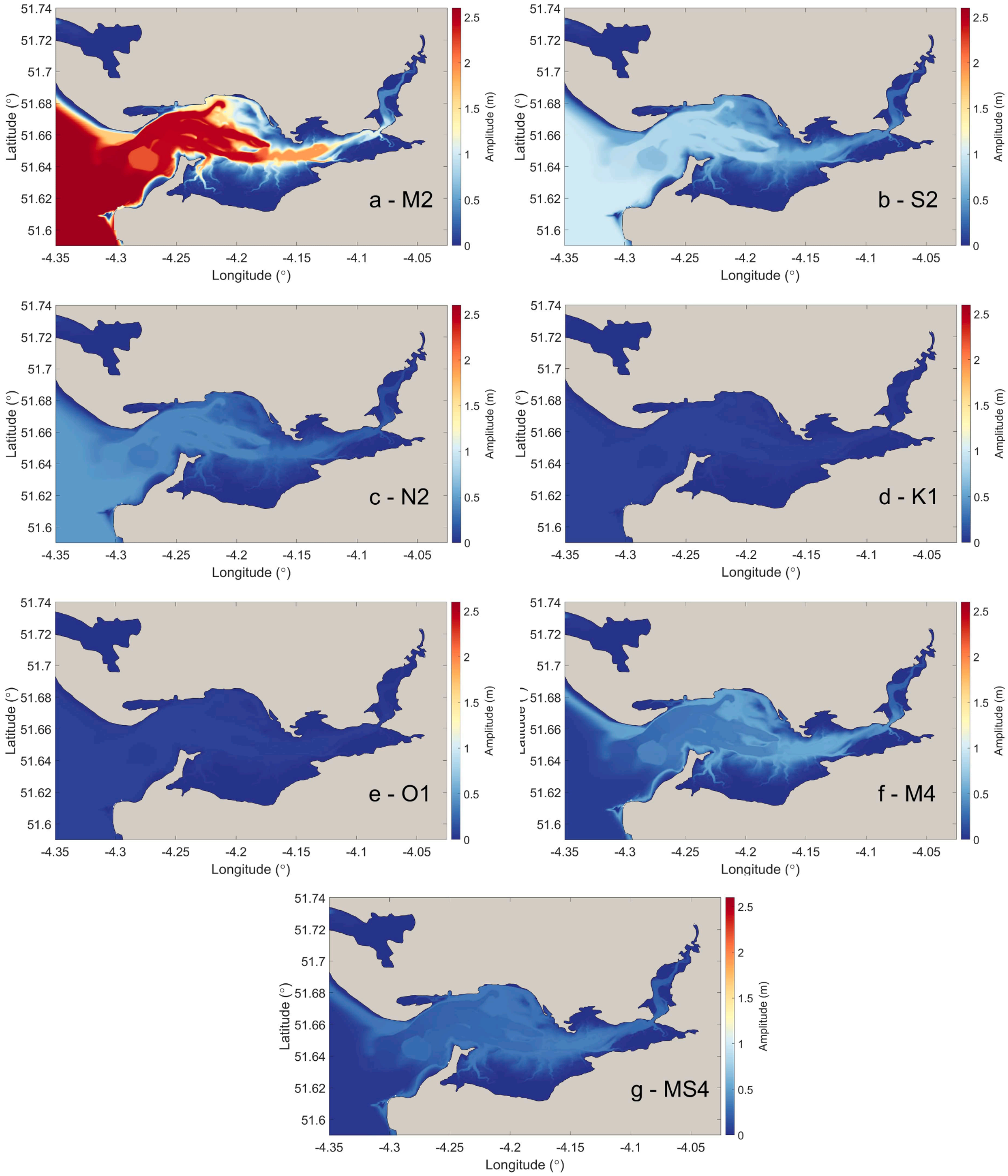

Fig. 9. Amplitudes of the important tidal constituents in Loughor estuary. **a** - M2, **b**- S2, **c** - N2, **d** - K1, **e** - O1, **f** - M4, **g** - MS4.

presence of marsh vegetation is shown in Fig. 11c. The current velocities are less than 0.2 m/s throughout the estuary with a few exceptions along the main tidal channel at the middle and lower estuary where the currents reached 0.4–0.5 m/s. This may be attributed to relatively unobstructed flow along the wide, unrestricted lower and middle estuary. In the locations where the largest residual current velocities were observed, the flow is influenced by either shallow sand flats (lower estuary) or impinging marshes which have the potential to amplify tidal asymmetry. The comparison of residual currents with and without marsh vegetation (Fig. 11d) shows that vegetation contributes to significantly increase the residual current velocities in the tidal channel (up to a maximum of 0.1 m/s or 50% from the non-vegetated state), implying that the impinging marshes contribute to increase tidal asymmetry, especially in the upper and middle estuary. This may increase sediment transport capacity in the tidal channel which can cause channel erosion (DEFRA/EA, 2002; Karunarathna and Reeve, 2008). Unlike in the Mawddach Estuary where marshes contributed to widespread, small changes to residual currents, most changes in the Taf are concentrated to the main tidal channels and the changes are significant.

In Fig. 11e, residual current velocities in the Loughor estuary at its present state with marshes covered with vegetation is given while Fig. 11f shows the difference in residual current velocities with and

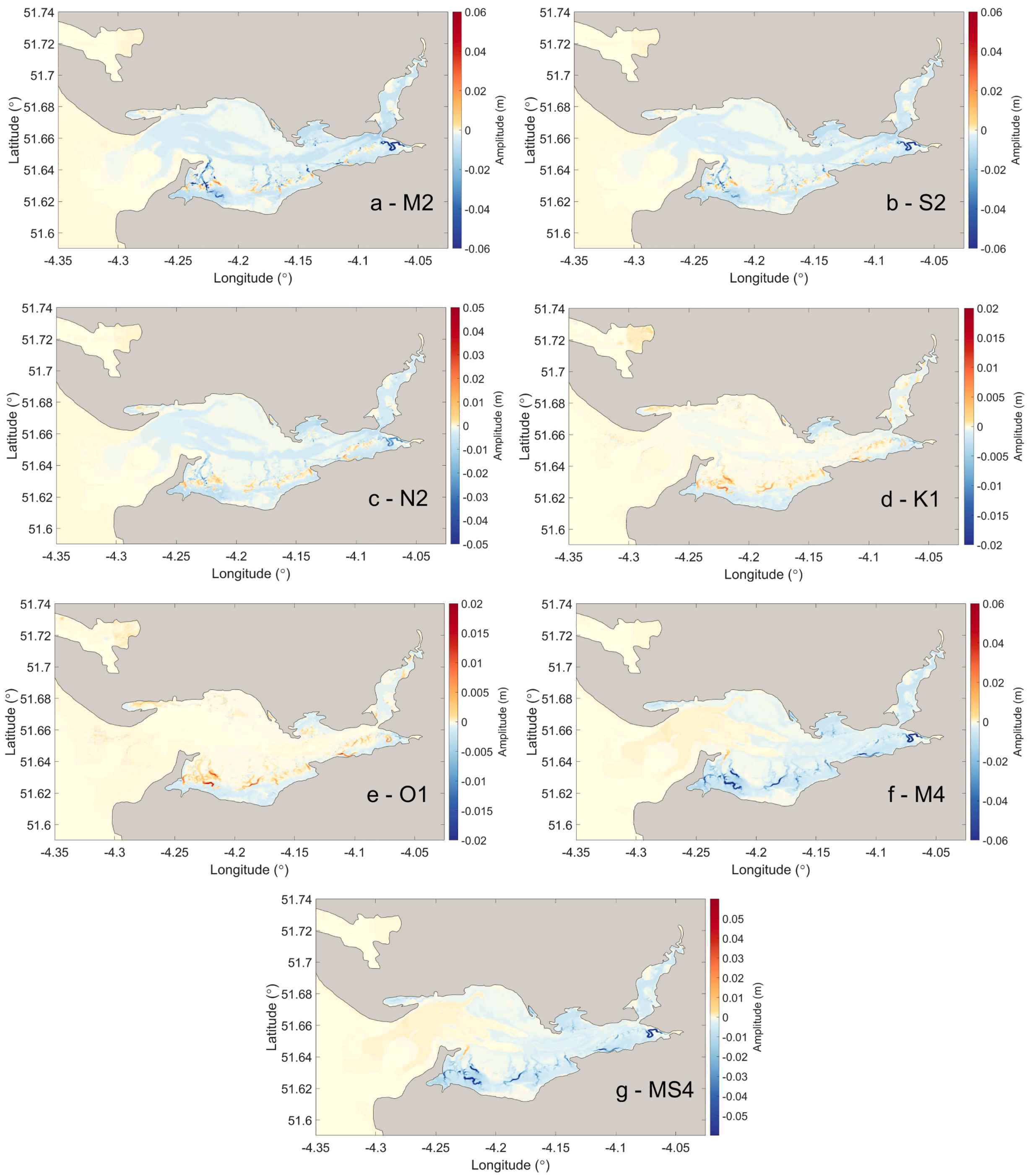

Fig. 10. Difference between tidal amplitudes with and without saltmarsh vegetation for tidal constituents M2, S2, N2, K1, O1, M4 and MS4 in the Loughor Estuary. **a** - M2, **b** - S2, **c** - N2, **d** - K1, **e** - O1, **f** - M4, **g** - MS4.

without vegetation cover. Residual currents are highest at the lower estuary where current velocities exceed 0.3 m/s at some locations. At two localised areas in the tidal channel in the middle and upper estuary the current velocity exceeds 0.7 m/s. Current velocity is less than 0.1 m/s in most intertidal areas outside the tidal channel in both middle and upper estuary. Residual currents are negligibly small in the upper estuary (< 0.03 m/s). These results show that the tidal asymmetry is smaller in the Loughor estuary. As seen in Fig. 11e marsh vegetation contributes to increase residual current velocities slightly in the main channel and notably in the tidal creeks. The largest increase of the residual current due to marsh vegetation in the tidal creeks in the lower and middle estuary is 65% while that in the main channel is less than 7%. In a few intertidal areas in the middle and upper estuary, a reduction of residual currents can be seen. Increase in residual velocity may lead to higher sediment transport capacity in tidal creeks which in-tern may contribute to erosion and migration of the creek network.

5. Discussion

Tidal dynamics of Mawddach, Taf and Loughor estuaries show some similarities as well as some distinct differences. The maximum flood and ebb currents were in the range of 0.6 - 1.5 m/s, which was found in the tidal channels. Both bb and flood tidal currents on marsh platforms were less than 0.1 m/s. Tidal asymmetry, due to shallow water dispersion

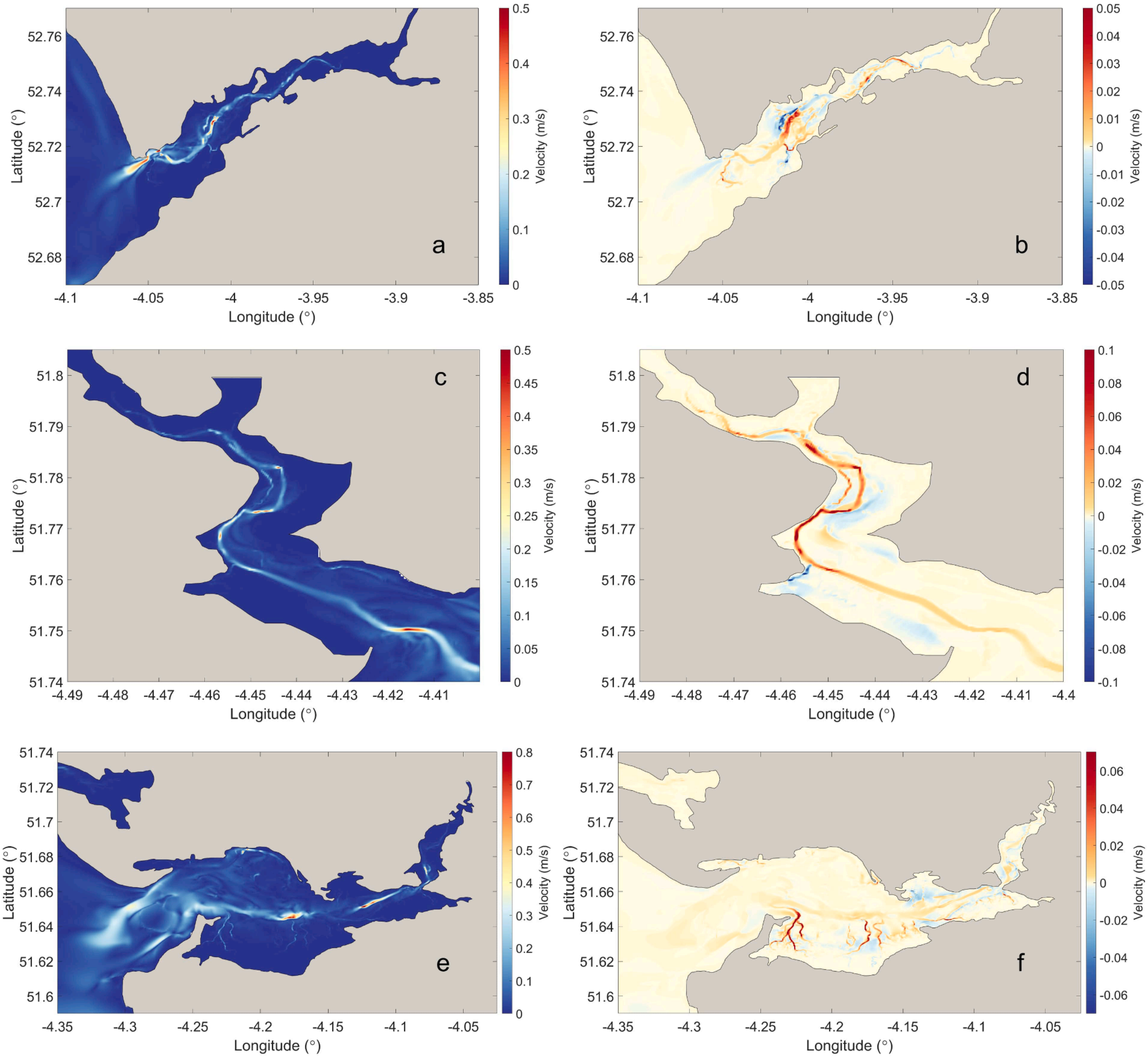

Fig. 11. Residual currents comparison for the Mawddach (**a**,**b**), Taf (**c**,**d**), and Loughor (**e**,**f**) estuaries. **a**,**c**,**e** - residual currents in the present state of estuary with vegetated saltmarshes. **b**,**d**,**f** - Difference of residual currents with and without marsh vegetation.

where flood flow is stronger than the ebb flow, is a common features amongst the three estuaries despite the differences in their size, shape and the tidal range. Both flood and ebb current receded The highest tidal asymmetry is found in the smallest Mawddach estuary with peak flood and ebb flows being 1.0 m/s and 0.6 m/s.

M2 is the most significant tidal constituent that governs the hydrodynamics in all three estuaries. Saltmarsh vegetation increases frictional drag which can alter tidal currents (Blanton et al., 2002) and hence tidal constituents. The influence of saltmarsh vegetation on M2 is evident irrespective of the size and shape of the estuary, tidal range and saltmarsh coverage. However, the vegetation-induced changes were highest at the Taf estuary (5–15%) although the percentage saltmarsh coverage compared to surface area is marginally higher in Mawddach than in Taf. The smallest impact is seen in the Loughor estuary (< 5%) where size is the largest and the marsh coverage is the smallest. Saltmarsh vegetation not only reduced M2 amplitude on marsh platforms but also on tidal channels and the surrounding areas of all estuaries. Those changes are more prominent in the upper-middle and the upper estuaries at all three sites where saltmarshes coverage is the largest. This result is in agreement with D'Alpaos et al. (2006) who observed reduction in tidal prism due to marsh vegetation thus resulting smaller tidal currents in channels.

The impact of saltmarsh vegetation on the other tidal constituents S2, N2, K1, O1, M4, and MS4 are varied amongst constituents and amongst the three sites. The semi-diurnal S2 and N2 amplitudes in the main tidal channels were reduced by of marsh vegetation. The largest reductions are seen in the upper and upper-middle estuary of all sites where saltmarsh coverage is the largest. This trend is very similar to the changes found in M2 amplitude. The diurnal K1 and O1 constituent amplitudes in the channels and some tidal flats of Mawddach and Loughor estuaries increased with the removal of marsh vegetation while it reduced in the smallest Taf estuary channel. Most changes are small compared to the changes associated with semi-diurnal constituents. Unlike S2 and N2 tides where most changes occur in the upper estuary, no significant differences can be seen in the lower, middle and upper estuaries at all three sites. Notable changes to the amplitudes of shallow water constituents M4 and MS4 are found in the upper estuary channel of Taf and Mawddach estuaries. The scale of changes are smaller but more widespread in Loughor. Most changes to M4 and MS4 areas are localized to areas where marshes are present unlike in the case of other constituents where changes were not limited to marsh areas and the surroundings.

Although some general trends of the impact of marsh vegetation on tidal constituents are observed, the results from the three estuaries reveal that those effects are not always localized to areas with marshes nearby (similar to the observation of Temmerman et al., 2007) and vary with the size of the estuary. However, the effects are more pronounced in the middle and upper estuary where most marshes are concentrated. Taf and Mawddach estuaries in which marsh cover is large compared to the surface area of the estuary had the strongest overall effect although the percentage saltmarsh coverage with respect to the total estuarine surface are not significantly different in all three estuaries.

In smaller estuaries where shallow water tidal constituents can grow gradually towards the middle and upper estuary, saltmarsh vegetation can play a significant role in offsetting the growth. This, together with the reduction of the amplitudes of the primary tidal constituents can be an important catalyst for reducing floods induced by high tides and surges during storm events, on which the impact of vegetation has been noted by other studies (e.g., Fairchild et al., 2021; Hu et al., 2015; Wamsley et al., 2010).

Vegetation effects on residual currents was notable where vegetation increased residual currents in the tidal channels, while reduced in the adjacent intertidal areas in Taf and Mawddach estuaries. The maximum increase of the residual currents in the tidal channel of the Taf estuary is 50% while that in Mawddach is 40%. Most changes to residual currents due to vegetation (up to 65%) in Loughor estuary are seen in some tidal creeks located in the middle and lower estuary saltmarshes. The direction of the residual velocities was not significantly altered in all three estuaries. As association of long term sediment dynamics with tidal residuals are well established (De Swart and Zimmerman, 2009; Moore et al., 2009) changes to residual currents may have potential implications on the long term morphodynamics of the whole estuary in small estuaries and localized morphodynamics of large estuaries. Reduction of residual currents in tidal channels and creeks may reduce the sediment carrying capacity while the opposite is true when residual currents are increased (Dronkers, 1986). This can lead to channel infilling/erosion and migration, which over a period of time, can alter the morphodynamics of the estuary. As small estuaries with significant saltmarsh coverage are impacted by the presence of saltmarshes to a higher degree, it is important to include marsh vegetation in the studies aiming at morphodynamic change of estuaries.

6. Conclusions

Three small estuaries in Wales, UK, Mawddach, Taf and Loughor, which have distinctly different characteristics and substantial saltmarsh cover with respect to the surface area of the estuary have been modelled to investigate the impact of saltmarsh vegetation on tidal dynamics of the estuaries. The numerical Delft3D modelling software was used in 2D mode to model the estuaries. The presence of saltmarsh vegetation alters the hydrodynamic regime, which was revealed through the changes to seven tidal constituents including five primary constituents M2, S2, N2, K1, O1, two shallow water constituents M4 and MS4, and residual currents. By analysing the tidal regime in detail and comparing marsh vegetation-impacted tidal flow regime against a baseline scenario without marsh vegetation, the following conclusions were drawn:

- Although the tidal range varies across the three estuaries, all three have semi diurnal tides and M2 is the predominant primary tidal constituent. The presence of notable shallow water tidal constituents M4 and MS4 indicates significant tidal distortion within all three estuaries.
- Saltmarsh vegetation reduces the amplitude of both primary and shallow water tidal constituents near and far-field of saltmarshes. Most changes observed outside marsh platforms were confined to tidal channels and the intertidal areas in the vicinity of channels, with only a very few exceptions. Smaller estuaries undergo larger changes.
- Presence of saltmarsh vegetation reduces altered tidal constituents in all three estuaries. The changes are more prominent and significant in the smaller Taf and Mawddach estuaries although all three estuaries contained similar marsh coverage when compared to the surface area of the estuary.
- Mawddach Residual currents in all three estuaries are largely confined to tidal channels although lower estuarine creeks in Loughor estuary show notable residual currents. Saltmarsh vegetation widely contributes to increased residual current velocities in tidal channels. The largest changes were seen in the smaller Mawddach and Taf Estuaries. The changes were smaller in magnitude and more wide spread over the whole estuary in Loughor estuary where the surface area is an order of magnitude larger than Taf and Mawddach.
- The influence of marsh vegetation on tidal constituents and residual currents signifies the importance of marsh vegetation loss or growth on estuary hydrodynamics and flood mitigation which in turn are important factors needed to be taken into account when using marshes for farming, tourism and other ecosystem service provisions.
- The results shown in this paper give useful insights for making decisions on saltmarsh conservation and, estuary and flood management, especially using nature-based solutions in small estuaries.

Open research

The data used in this study, and the model outputs, are archived in the "Saltmarsh Vegetation Alters the Tidal Hydrodynamics of Small Estuaries" Zenodo repository and are accessible at 10.5281/zenodo.5906709.

CRediT authorship contribution statement

W.G. Bennett: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **J.M. Horrillo-Caraballo:** Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **T.P. Fairchild:** Methodology, Validation, Resources, Writing – review & editing. **T.J. van Veelen:** Methodology, Validation, Resources, Writing – review & editing. **H. Karunarathna:** Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

Harshinie Karunarathna reports financial support was provided by Natural Environment Research Council.

Data availability

The data used in this study, and the model outputs, are archived in the Zenodo repository and are accessible at https://doi.org/10.5281/zenodo.5906709.

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