Coastal flood alleviation through management interventions under changing climate conditions

Structured Abstract

Purpose of this paper	Coastal flooding has disastrous consequences on people, infrastructure, properties and the environment. Increasing flood risk as a result of global climate change is a significant concern both within the UK and globally. To counter any potential increase in future flooding, a range of potential management options are being considered.
Design/methodology/approach	The Taf estuary in South West Wales, a macro-tidal estuary which has a history of coastal flooding, was chosen as the case study in this paper to investigate the impact of coastal management interventions such as construction of hard defences , managed realignment, or altering land use of affiliated ecosystems such as salt marshes on the complex hydrodynamics and hence flooding of the surrounding areas of the estuary. The study was carried out using a numerical hydrodynamic model of the Taf estuary, developed using the process-based Delft3D modelling software.
Findings	The role of the selected management interventions on coastal flooding was investigated using an extreme storm condition, both with and without the impact of future sea level rise. The results highlight the scale of the effect of sea level rise, with the selected management interventions revealing that minimising the increase in flooding in future requires careful consideration of the available options.
What is original/value of paper	This paper explores the highlighted role of coastal management practice in future with the influence of climate change to study how effective alternative methods can be for flood alleviation.

1. Introduction

Coastal communities are at increasing risk of flooding and erosion as a result of frequent occurrences of extreme storms and rising sea levels forced by global climate variabilities. The 2013/14 winter storms, which threatened safety of people and, damaged houses and millions of pounds worth coastal infrastructure in the UK and around Europe, highlighted the need for long term coastal flood and erosion risk mitigation and management interventions. Current sustainable coastal management legislation stresses the need to develop coastal and flood defense solutions which do not negatively interfere with the natural environment. As a result, managed realignment is increasingly favored, thus creating new intertidal areas that act as buffer zones against coastal flooding. Natural coastal ecosystems such as salt marshes, mangroves and coastal wetlands can also act as natural barriers against storm waves. They can help reduce the need for hard defenses against flooding and erosion and lessen the effect of wave action on coastal infrastructure.

Combination of more natural and engineered approaches, which are known as 'nature-based coastal defence approaches' have been identified as desirable solutions against coastal flooding and erosion as opposed to hard coastal defences alone. Salt marshes have been found to act as natural buffer zones, providing protection from storm waves and flooding (Temmerman et al., 2013). In addition, salt marshes can help reduce vulnerability of hard defences to bed scour and erosion (Dixon et al., 2008), and lessen the effects of wave action on the structure (Möller et al., 2001). Thus, a saltmarsh combined with a coastal defence may reduce the size and height of a seawall required to manage a coastline, with a near-linear relationship between saltmarsh width and seawall height for comparable levels of protection (King and Lester, 1995; Dixon et al., 1998; Bouma et al., 2014).

Catastrophic events such as Tsunami are not commonplace within the UK, although there is some debate that a Tsunami occurred in the Bristol Channel in January 1607 (Bryant and Haslett, 2007). Storms however, are more frequent and have historically had severe impacts, which although not on the same scale as tsunami, are considerable. For example, the 1953 North Sea flood along the east coast of England forced 24,000 people out of their homes and led to the deaths of 307 people, alongside significant financial costs (Baxter, 2005). A storm surge occurred in December 2013 resulted in 10 deaths and incurred 1.9 billion Euros worth of insured losses across the UK, The Netherlands and Denmark (Spencer et. al., 2015).

In this paper, we compare the impact of three fundamentally different management intervention strategies for flood mitigation during extreme storm events in the small-microtidal Taf estuary, through a computational modelling study. Villages and towns at close proximity to the Taf estuary repeatedly and regularly flood during storms, thus disturbing the lives and livelihoods of these coastal communities. Understanding the impact of management interventions on flood of alleviation under present and future climate conditions is fundamental for long term sustainable coastal management. The paper is structured as follows: Sections 2 and 3 describe the case study area, and the methodology used to determine extreme storm conditions and the modelling approach respectively. The results and discussion are given in Sections 4, with conclusions drawn in Section 5.

2. Case Study

The Taf is a small estuary (8.65 km^2) situated within Carmarthen Bay in South West Wales, UK (Figure 1). The estuary is macro-tidal with a mean spring tidal range of 7.5 m , a neap tidal range of 3.7 m (Ishak, 1997) and a tidal prism of 17.7 $\times$ 10^6 m^3 (Bristow and Pile, 2003). It is a funnel shaped sinuous estuary (Cousins et al., 2008) and at high water, it is tidal to an extent of 15km upstream from Carmarthen Bay (Pye and Blott, 2009). Currents within the estuary are at a maximum as the sea enters the estuary and before it retreats, with peak tidal currents reaching 2.2 m/s (Ishak, 1997). The river Taf has an average daily freshwater discharge of 7.0 m^3/s with an extreme high of 60 m^3/s during winter months and extreme low of 0.6 m^3/s occurring during summer months (Halcrow, 2012). Within Carmarthen bay swell waves are predominantly south westerly, with a fetch length of up to 6000km (Pye and Blott, 2009). Swell wave penetration into the estuary is limited by the orientation of the mouth of the estuary (Pye and Blott, 2009). However, locally generated wind waves within the estuary can be significant and have a wider array of directions.

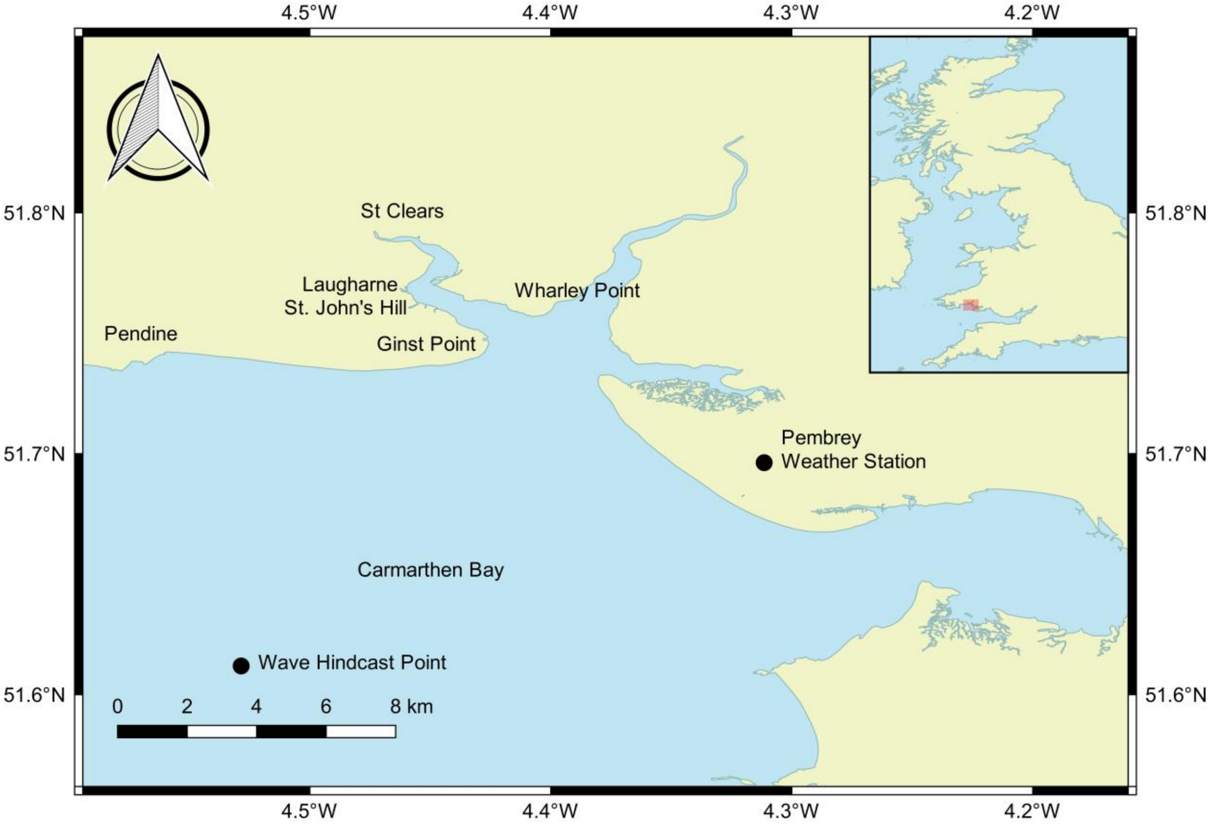

Figure 1 - Overview of Carmarthen Bay highlighting key locations, and its location within the UK (red box).

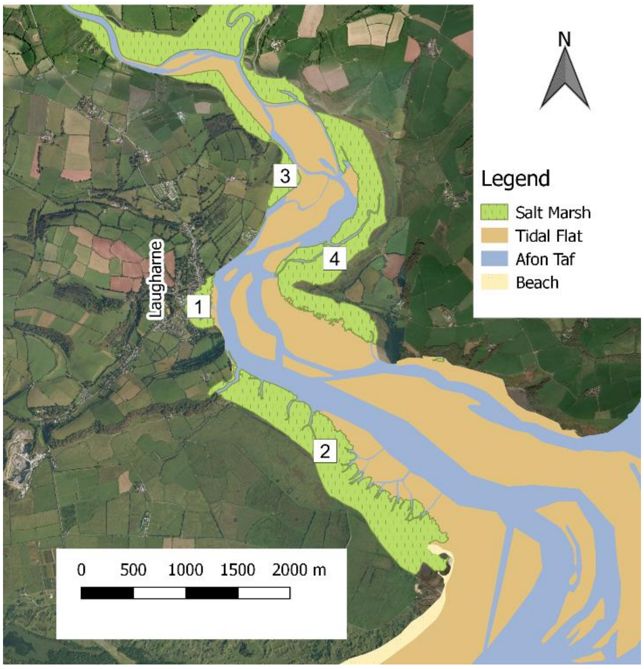

Figure 2 - Overview of the Taf Estuary. Numbers 1, 2, 3, and 4 denote Laugharne Castle, Laugharne South, Laugharne North, and Black Scar marshes respectively.

The Taf represents a typical Welsh estuary in terms of size, tidal characteristics and morphodynamic features. Within the estuary there exist several different environments such as sand flats, mud flats, and saltmarshes (Figure 2) (Jago, 1974). There are four main areas of saltmarsh (Figure 2), Laugharne Castle, Laugharne South, Laugharne North, and Black Scar, occupying a total area of 279 ha (Bristow and Pile, 2003). Ginst point and Wharley point are of importance (Figure 1), restricting the estuary mouth from the southwest and the northeast. The historic village Laugharne, located at the fringe of one of the largest marshes of the estuary, which regularly floods during winter storms, attracts the attention of policy makers and coastal managers as there is an urgent need to implement a sustainable flood prevention solution to protect the village. The current management policy in the Taf estuary is to allow the natural development of undefended shores, and to reduce the risk of flooding and erosion (Halcrow, 2012). This results in an array of policy decisions depending on the assets at risk, and the time frame considered. For the eastern bank of the estuary, and the western bank north of Laugharne, no active intervention is chosen. However, to protect the village of Laugharne and further south, a mixture of managed realignment and hold-the-line policies are utilised.

3. Methodology

3.1 Storm boundary conditions

To investigate the impacts of different estuary management intervention scenarios on flood alleviation within the Taf estuary during extreme events through computational modelling, it is necessary to derive storms that may have significant implications on the estuary and the surroundings. Here, storm conditions are defined by extreme wave, wind and water levels (tides and storm surge).

3.1.1 Waves

Wave hindcast data for Carmarthen bay was provided by the Centre for Environment Fisheries & Aquaculture Science of the UK (CEFAS) hindcast dataset. Data for Carmarthen bay was extracted from the nearest hindcast output (Figure 1), providing wave characteristics for the period 1980-2017. The wave dataset was filtered to identify storm conditions following the approach described in Bennett et al. (2016). The method uses the storm event definition of Dissanayake et al. (2015), taking a storm wave height threshold of 2.5m, based on the UK Channel Coastal Observatory (CCO) guidance (www.channelcoast.org/reports/). The Generalised Pareto Distribution (GPD) was used to determine extreme wave heights for a range of storm conditions. The GPD was fit to the peak storm wave heights, with the GPD given in Equation 1 (which is the combination of three statistical families), and the method of Hawkes et al. (2002) was used. In Equation 1, φ and ξ are scale and shape parameters respectively (Coles, 2001) and u is the threshold that ensures model convergence. The R statistical software package ismev (Coles, 2001) was utilised to fit the GPD to the data (R Core Team, 2013).

$$Pr\{X > x | X > u\} = \begin{cases} 1 + \xi\,\phi^{-1}\,(x-u)^{-1/\xi} & \xi \neq 0 \\ e^{-\frac{x-u}{\phi}} & \xi = 0 \end{cases} \tag{1}$$

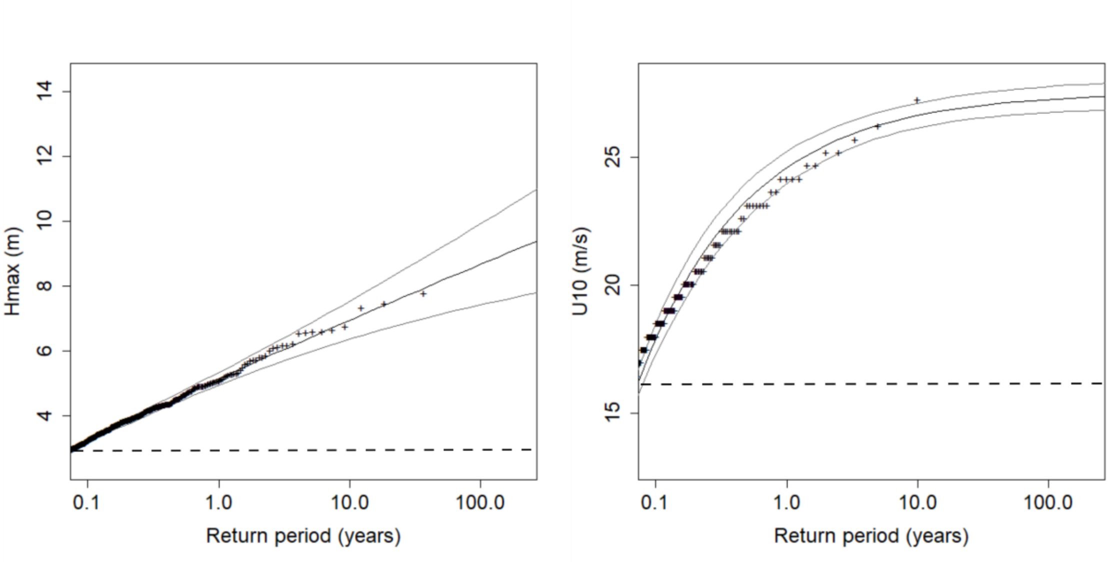

Figure 3 - GPD profiles for wave height (left) and wind speed (right). Crosses indicate storm significant wave height and wind speed values, with the GPD fit and 95% confidence intervals indicated by the three curves. Dashed line indicates the threshold level.

The significant wave height of storms corresponding to 1 in 1, 10, 50, and 100-year return periods were derived from the GPD (Figure 3). The average storm significant wave height was taken as the average value from the filtered storm conditions. The maximum storm wave period (T_{max}) as determined from the average of the (T_{max}) values for individual storms extracted from the hindcast data. The predominant direction across all the individual storm events was used as the storm incident direction (Wd_{avg}). These conditions are summarised in Table 1.

	Average Storm	1 in 1 year	1 in 10 year	1 in 50 year	1 in 100 year	Wd_{avg} (degrees)	T_{max} (s)
Significant Wave Height (m)	3.37	5.13	6.94	8.15	8.66	225	6.82
Wind Speed (m/s)	16.75	24.59	26.64	27.15	27.27		

Table 1 - Summary of statistically significant storm wave boundary conditions in Carmarthen bay. T_{max} is the maximum storm wave period, and Wd_{avg} is the predominant storm wave direction.

To provide corresponding wind forcing required for the computational model, wind outputs from the nearby Pembrey weather station (Figure 1) were utilised, providing hourly wind records for the period 2002-2009. As with the wave data, the GPD was fitted to the wind data. The predominant wind direction was determined from the observed wind data during storm conditions. The return level plot for the storm wind velocity is shown in Figure 3, with wind speeds with different return periods summarised in Table 1.

Time varying wind and wave conditions during a storm were created through the use of a representative storm profile. A three-point spline curve, which closely represents observed storm profiles, was used. In the storm profile developed in this manner, the storm begins when incident wave height exceeds the pre-selected threshold wave height and ceases when the wave height becomes smaller than the threshold. The storm peaks halfway between the beginning and the end of storm thus creating a symmetric storm wave height profile. The corresponding wind conditions for the chosen storm wave return period follow the same three-point spline shape.

3.1.2 Water Levels

Statistically significant water levels during storms are obtained based on McMillan et al. (2011). Using data supplied by the National Tide and Sea Level Facility of the UK (NTSLF), they performed a statistical analysis to determine peak water levels and storm water level profiles using the Skew Surge Joint Probability Method (SSJPM) for 40 of the UK national network (class A) of tide gauge sites from around the coastlines of England, Scotland and Wales, together with equivalent data from 5 other primary sites. Their analysis provides sea levels with a range of return periods at 2km spacing around the UK coastline. During extreme events, the total water level is a combination of the astronomical tide and the storm surge. Scaled surge shapes, such as the one for Mumbles tide gauge shown in Figure 4, have been derived following the method they used in their analysis. This allows derivation of appropriate total water level curves, thus incorporating the increase and decline of surge during the extreme event. The guidance provided by McMillan et al. (2011), suggests that the base astronomical curve should be halfway between the Mean High Water Spring tide (MHWS) and Highest Astronomical Tide (HAT), in this case 4.35m Ordnance Datum (OD). This was also utilised as the average storm water level for the analysis.

To create the final water level profiles for the desired range of storm conditions, the peak storm water level was combined with the time-varying surge profile for each return period to scale up the base astronomical curve (Figure 4). The peak storm water level conditions are summarised in Table 2. In this analysis we assume that the storm peak coincides with high tide and the maximum surge occurs at the peak of the storm to represent the worst-case extreme event scenario.

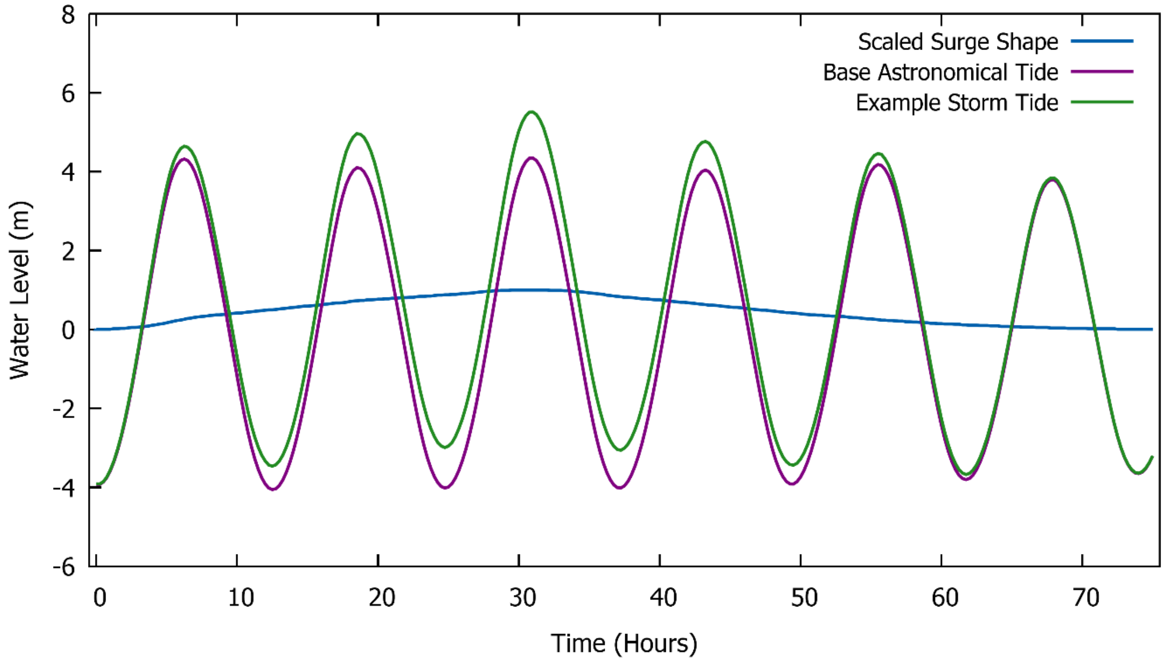

Figure 4 – An example of surge profile (McMillan et al., 2011), base astronomical tide and the storm tide at Carmarthen Bay.

	Average	1 in 1 year	1 in 10 year	1 in 50 year	1 in 100 year
Peak sea level	4.35	5	5.26	5.43	5.51

Table 2 – Peak storm water levels in Carmarthen bay, determined following McMillan et al. (2011).

To calculate future storm water levels, the impact of sea level rise was added to the storm water level curve calculated for present climate conditions. Regional relative sea level rise for Carmarthen Bay was extracted from the United Kingdom Climate Projections 18 (UKCP18) marine dataset (Palmer et al., 2018). Projected changes at 12km intervals were extracted for the 50th percentile of the Representative Concentration Pathway (RCP) 4.5 scenario (Moss et al., 2010) from 2007 to 2100. This provided a relative sea level rise value of 0.444m between 2017 and 2100. The future 1 in 100 year peak storm water level was thus calculated as 5.954mODN.

3.2 Modelling Approach

The area computational coastal modelling suite Delft3D (Lesser et al., 2004) was used to investigate changes in estuary hydrodynamics due to differing coastal saltmarsh management scenarios. The Delft3D can simulate the interaction between water, sediment, ecology and water quality and has been extensively used within industry and research communities since its initial development to investigate coastal erosion and inundation problems. Examples of the range of use include efforts to model the effect of beach nourishment on the northern part of the Dutch coast (Grunnet et al., 2004), an investigation of the effects offshore wind farms have on surface waves and circulation in Lake Ontario (McCombs et al., 2014), coastal erosion and flooding in Sefton, UK (Dissanayake et al., 2014, 2015, Bennett et al., 2019) and work to understand the effect vegetation and wetlands have on storm surge levels in south-eastern Louisiana (Hu et al., 2015). Delft3D allows for the implementation of various features, including vegetation characteristics, differing sediments, and hard defences, which are key to accurately capturing the Taf estuary. The model will provide waves and hydrodynamics of the estuary and captures the impacts of river flow, salt marsh ecology and wave-current interactions on hydrodynamics. The Taf hydrodynamic model encompasses the majority of the Taf estuary, extending out in to Carmarthen bay to a depth of 22m (Figure 5), to capture undisturbed water levels and waves.

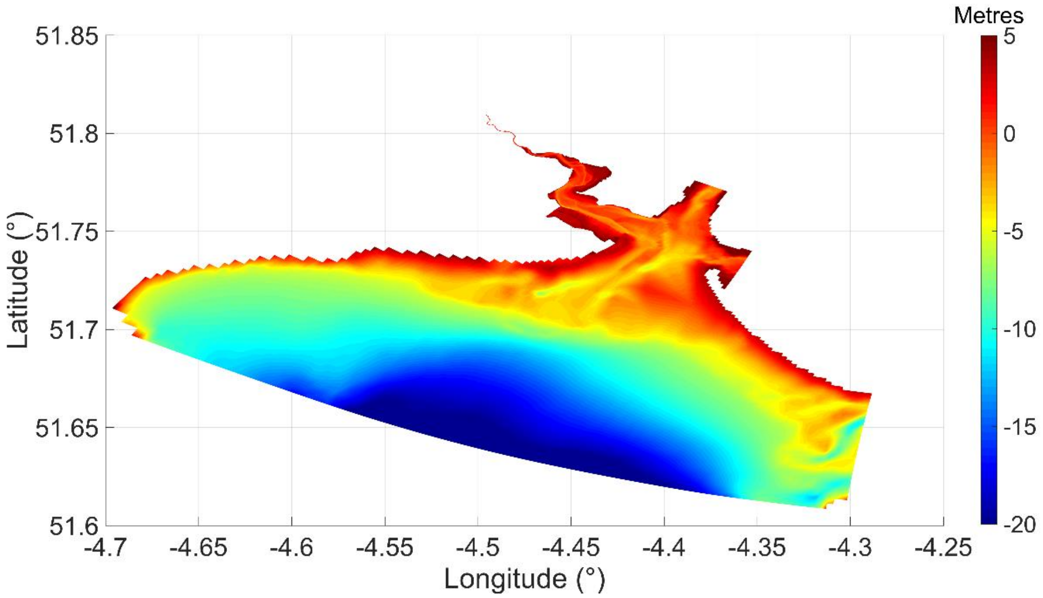

Figure 5 - Taf estuary model domain. Model grid covers the Taf estuary and three river confluence, extending in to Carmarthen bay. Colour bar in metres.

The model bathymetry was created through combining data from the UK Hydrographic Office (UKHO) at 2m resolution from 2013, Admiralty charts data from 1977, and from new high-resolution bathymetric surveys carried out within the estuary during this study.

Salt marsh vegetation is modelled with plant geometry simplified as rigid cylinders that are parameterized by plant height h_v, stem diameter (b_v) and plant density (n_v) (Dalrymple et al., 1984). The drag coefficient (C_D) is the only parameter that cannot be measured in the field a priori. Therefore, the value $C_D = 1$ is selected based on experimental studies with stiff cylinders in unidirectional flow (Tanino and Nepf (2008)) and waves based on conditions in the Taf estuary (van Veelen et al., 2019). $C_D = 1$ was also successfully applied in recent modelling studies (Ashall et al., 2016; Hu et al., 2018). Finally, the river discharge is set to represent the most extreme conditions observed in the Taf, providing the worst case storm scenario. Specifically, it has been set at a constant discharge of 60 m^3/s, which is the highest measured discharge (Ishak, 1997).

Parameter	**Symbol**	**Value**	**Unit**	**Motivation**
Plant width	b_v	2.58*	mm	From field measurements
Plant height	h_v	34	mm	From field measurements
Plant density	n_v	2275	m^{-2}	From field measurements
Drag coefficient	C_D	1.0	-	Tanino and Nepf, 2008; van Veelen et al., (2019)
Bed roughness	C_b	65	m$^{1/2}$/s	Marciano et al., 2005
River discharge	Q	60	m^3/s	Ishak, 1997
Water density	ρ_0	1025	kg/m^3	Well-mixed estuary
Horizontal eddy viscosity	K	1	m^2/s	Mariotti and Canestrelli, 2017

Table 3 – Vegetation model input parameters

Acoustic Doppler Current Profiler (ADCP) and current meter data from deployments in the Taf were used to validate the numerical model. The ADCP was deployed for 10 tidal cycles between 10th and 16th of June 2018 in the main channel of the estuary. The tidal model was run for the corresponding period. The coefficient of correlation, $r^2 = 0.88$, and Nash-Sutcliffe efficiency coefficient, $NSE = 0.78$ (Nash and Sutcliffe, 1970), show good agreement between the model results and measured water depths in phase and amplitude. A single point current meter was deployed in the main channel upstream of Laugharne Castle marsh between 1pm on 28th November 2017 and 2:45pm on 30th November 2017. Despite issues with grounding of the meter on the tidal flats, comparison between flow velocities with modelled results show reasonable agreement. A coefficient of correlation $r^2 = 0.68$ and $NSE = 0.48$ indicate that the model predicts accurately flow velocities within the estuary.

3.3 Management Intervention Scenarios

Three different interventions; managed realignment, marsh grazing and construction of hard defences, were introduced to the saltmarsh areas of the estuary in the computational model including both ‘hard’ and ‘soft’ engineering options. The impacts under each intervention on hydrodynamics and flooding were discussed through a comparison of ‘current’ hydrodynamic regime under ‘present’ climate and, ‘future’ (end of century) climate.

Managed realignment involves altering breaching or complete removal of existing flood defences to increase flood accommodation space. Two potential areas for managed realignment have been identified within the Taf estuary (Figure 6) (Cousins et al., 2008). The two areas are currently privately-owned agricultural land. Mwche and Mylett farm sites provide 77.71 Ha of land for potential realignment through breaching of the existing defences (locations indicated in Figure 6). To implement managed realignment within the model, the existing flood defences were artificially breached, following the advice of Bristow and Pile (2013). The size of the breach is determined such that it does not lead to undesired morphological effects due to significant flow velocities through the breach. The method described in Leggett et al. (2004) was used to determine the breach width, based on the subsequent increase in tidal prism each location. The increase in tidal prism for Mylett and Mwche farm sites was estimated as 107,750 m^3 and 46,350 m^3 respectively (Cousins et al., 2008). Using these values provided breach widths of 46 m, and 41 m for the two sites. The breaches at both sites were placed at the end of existing creek networks, and near the locations of relic creeks from the reclaimed saltmarsh. These creek systems were then connected through lowering of the bathymetry either side of the breach.

Figure 6 – Proposed Taf estuary managed realignment sites indicated by Cousins et al. (2008). Numbers 1 and 2 indicated Mwche and Mylett farm sites respectively. White squares indicate breach locations.

The second scenario encompasses the impact of grazing of saltmarshes by local livestock, which is a common phenomenon in most Welsh estuaries. It will however reduce the vegetation height, and subsequently the resistance to wave and flow propagation on the marsh, diminishing their flood defence function (Davidson et al., 2017). To investigate the wider impacts of saltmarsh grazing in the Taf estuary, the extreme case in which all saltmarsh areas are grazed, was investigated. Grazing was introduced into the model by artificially removing the vegetation cover from the marshes, which replicates the extreme scenario.

Finally, a surge barrier to protect the village of Laugharne from flooding is investigated. Although a barrier is likely to eliminate flooding, It has been the subject of debate, and has been rejected by the local communities because of the fears of the aesthetic impact of such a measure (Halcrow, 2012). To investigate the potential impacts that a surge barrier may have within the estuary a thin dam was implemented within the model at the boundary of Laugharne. This prevents any flow from entering the village due to waves or water level.

Results & Discussion

Each flood defence intervention scenario mentioned in Section 3 was modelled during both the ‘present’ and ‘future’ 1 in 100 year storm to investigate the differences of their impacts alongside the current estuary configuration with relative sea level rise.

Firstly, the peak storm water level in the Taf estuary and the water level differences due to the selected management intervention scenarios during ‘present’ storm condition are shown in Figure 7. For the current state of Taf estuary, without any interventions, the tidal extent during the peak of the storm reaches the landward edges of the marshes, with water depths in the range 1-2 m. In the defended case, the hard defence at the boundary of the village of Laugharne causes little change in the overall estuarine peak storm water level. While the structure reduces the water depths behind the structure to zero, there are otherwise no noticeable changes. The effect of marsh grazing causes no significant change in water level. Due to the breaches in the managed realignment areas, there are large differences in water level between undisturbed and managed realigned sites. There are no significant wider difference seen outside of the marsh areas of the estuary however.

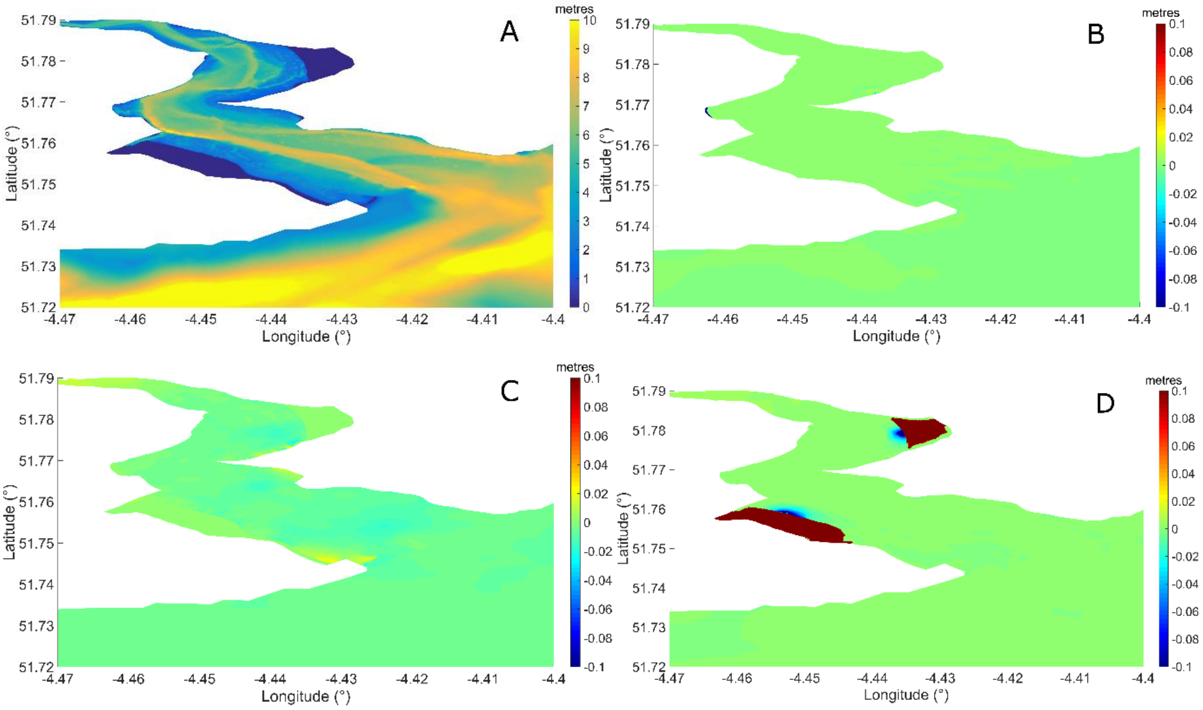

Figure 7 – Comparison of peak storm water depths at the Taf estuary under the selected intervention scenarios during the ‘present’ 1:100 year storm. a) Current condition, b) difference between defended and current c) difference between grazed and current d) difference between managed realignment and current.

The change in wave height in the estuary for the chosen interventions for the ‘present’ climate storm are shown in Figure 8. Without any interventions, for the current configuration in the Taf, the largest wave heights are seen in the areas around the mouth of the estuary (~1.4m). At the edges of the marshes, close to the tidal channel location, wave heights reach 0.6-0.7m, while those on the marshes reduce to less than 0.2m. It should be noted here that during westerly storms, local waves are generated within the estuary due to strong westerly winds and therefore, wave climate in the estuary is complex. The hard defence at the landward edge of Laugharne marsh causes very small changes in wave height coincident with the channel at the seaward boundary of the marsh, with a maximum difference of 0.06m. With the reduction in wave attenuation due to the lack of vegetation due to grazing, the wave heights within the estuary are generally increased. Wave height change on marsh areas are noticeable with a maximum of 0.1m increase, however within the channel system reasonable increases are seen (~0.02-0.05m). Similar to the grazed case, managed realignment causes a general increase in wave height throughout the estuary. Other than the intervention with hard defences, the other two intervention scenarios increased the wave height on the marsh by around 0.1m, which may be significant in terms of flooding and marsh erosion.

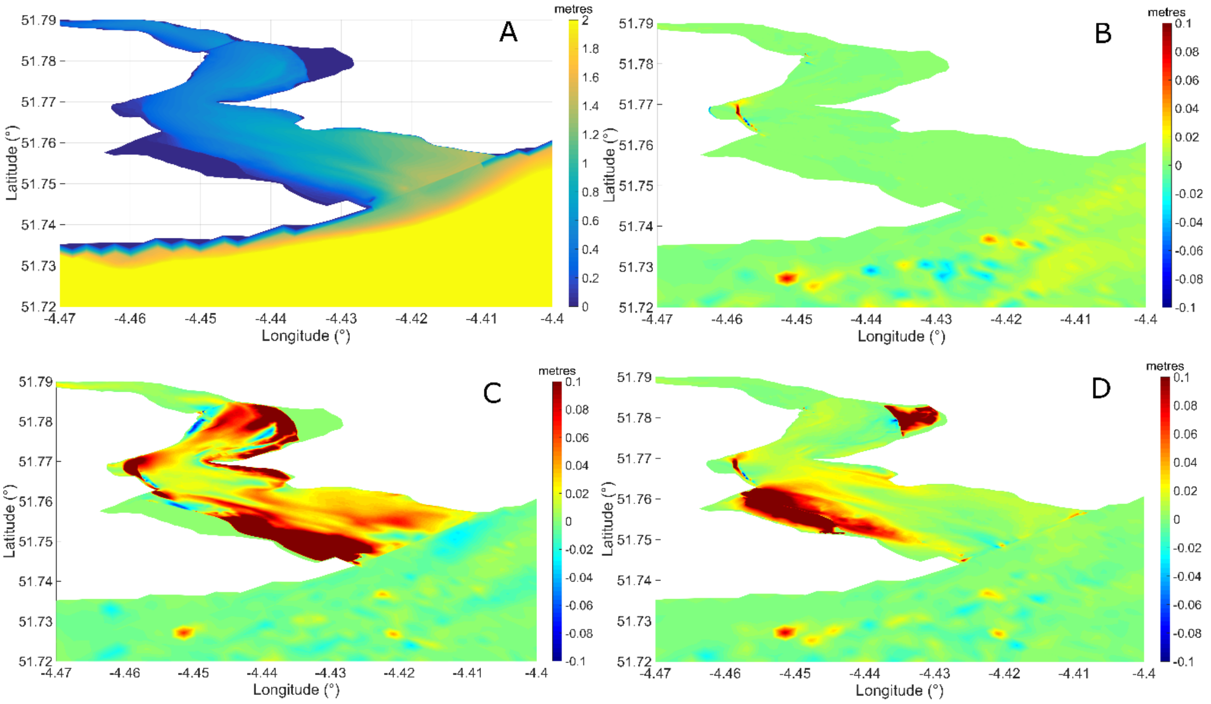

Figure 8 – Comparison of peak storm wave height at the Taf estuary under the selected intervention scenarios during the 'present' 1:100 year storm. a) Current condition, b) difference between defended and current c) difference between grazed and current d) difference between managed realignment and current.

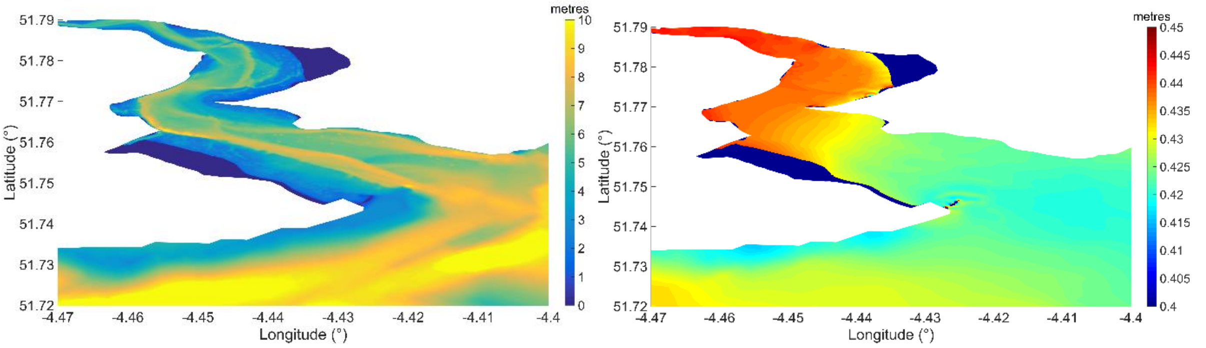

Figure 9 – Peak storm water depth under the 'present' current condition alongside the different due to the increase in sea level rise.

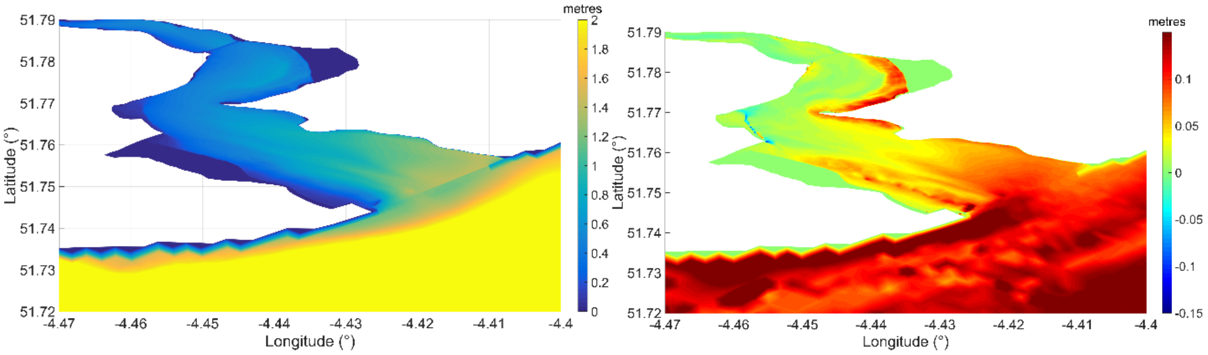

Figure 10 – Peak storm wave height under the 'present' current condition alongside the different due to the increase in sea level rise.

In Figures 9 and 10, the impact of sea level rise on the peak water depth and wave height for the current situation in the Taf estuary is highlighted. The change in water level in future is clear (Figure 9) with a fairly consistent increase across the estuary mouth of the estuary and into the bay, with a slight increase towards the mouth of the estuary. The funneling effect of the estuary is such that while the increase in water level is ~0.42m at the estuary mouth it is over 0.01m higher closer to Laugharne further up the estuary. While the wave height outside of the estuary increases significantly in future (Figure 9), the increases within the estuary are not as large. Within Carmarthen Bay, and near the mouth of the Taf the peak wave height difference between present and future is approximately 0.15m. Within the estuary, and across the marshes this is less but not insignificant, with increase between 0.05-0.1m across marsh areas and less than 0.05m offshore of the marshes. This may be due to the increase in water level reducing the role of attenuation from vegetation, as well as allowing waves to propagate and grow further onshore.

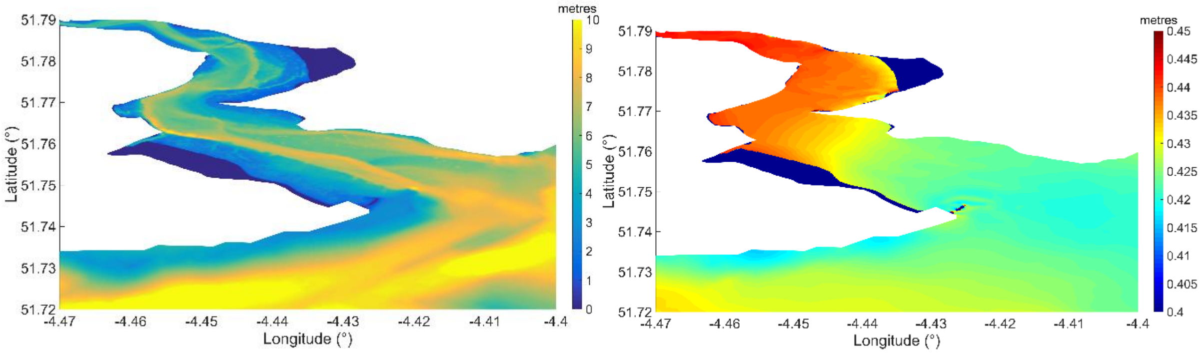

Figure 11 – Peak storm water depth under the 'present' defended condition alongside the difference due to the increase in sea level rise.

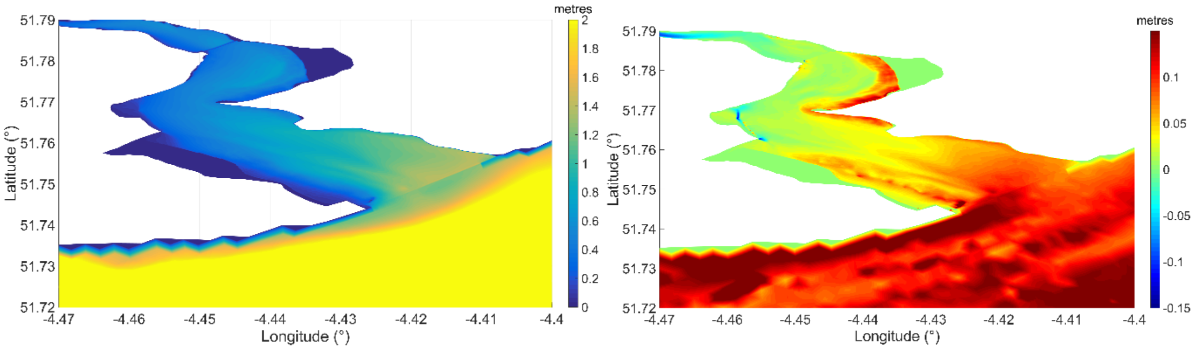

Figure 12 – Peak storm wave height under the ‘present’ defended condition alongside the difference due to the increase in sea level rise.

The differences due to the introduction of a hard defence with the influence of sea level rise are shown in Figures 11 and 12. The change in water level is again consistent with the impacts observed in Figure 8, a consistent increase across the estuary. While the hard defence prevents any increase in water level from impacting the village of Laugharne, it does not affect the overall pattern of water depth within the Taf. The change in wave height with the impact of sea level rise is similar to that shown under the current condition (Figure 10), highlighting the lack of impact of the hard defence on estuarine hydrodynamics. Whilst it doesn’t have any effect on the wider behavior compared with the current condition, it does eliminate the flood risk to Laugharne.

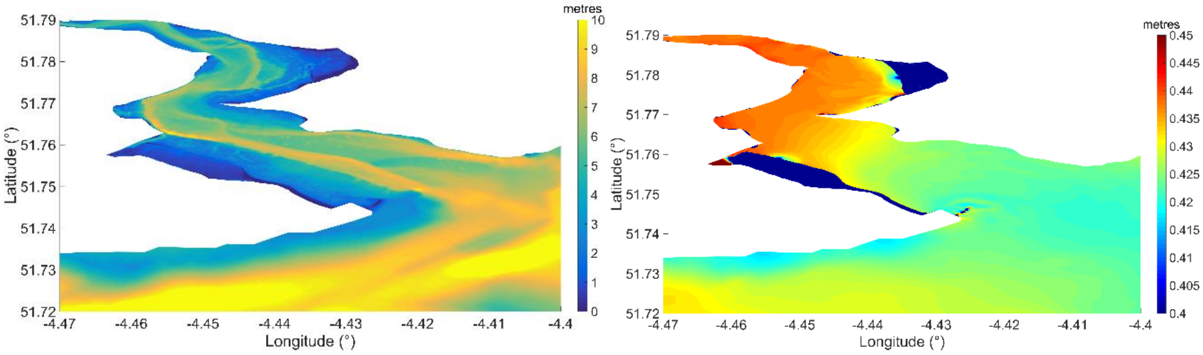

Figure 13 – Peak storm water depth under the ‘present’ managed realignment condition alongside the difference due to the increase in sea level rise.

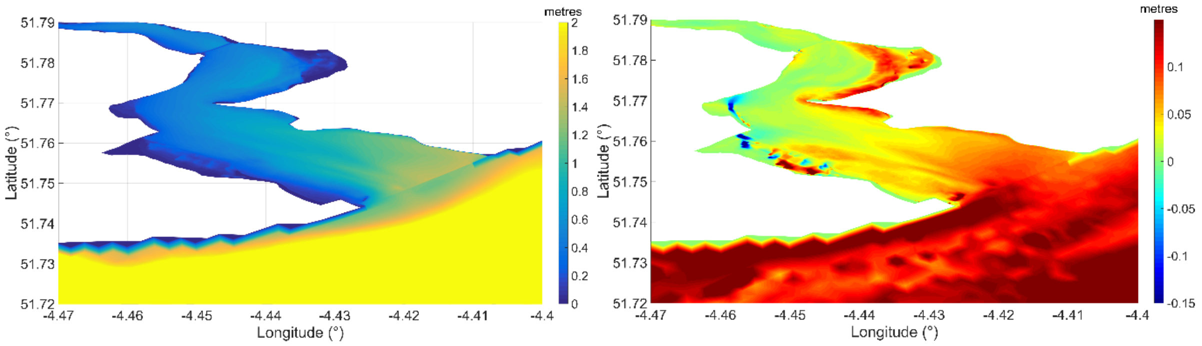

Figure 14 – Peak storm wave height under the ‘present’ managed realignment condition alongside the difference due to the increase in sea level rise.

Under the managed realignment intervention, the influence of sea level rise shows a similar pattern to Figures 9 & 11, although not wholly consistent. The increase in water towards the mouth of the estuary is very slightly reduced due to water being redirected at the two sites. Within the two areas as water is introduced, compared with the present condition the increase in water level is much less than that within the estuary and in the bay. The lower increase in the realignment areas may help in providing space for saltmarshes to rollback to, which is important for management policy. However, it does not help with flood alleviation for Laugharne. Compared with the current configuration changes, the differences in wave height outside of both realignment sites is very similar (Figure 14). Within the two sites there is a noticeable increase in wave height, linked with the increase in water depth. Due to the orientation of the two sites with respect to the predominant wind direction, it does not impact upon the wave energy within the main channels of the estuary.

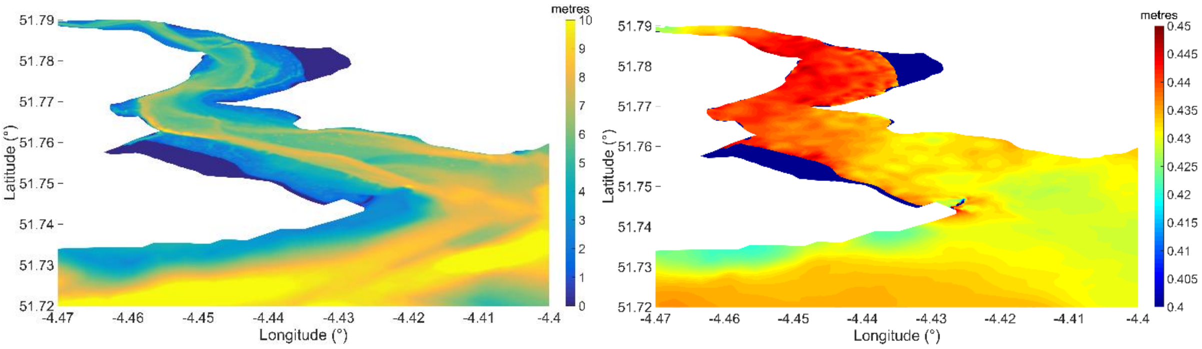

Figure 15 – Peak storm water depth under the 'present' grazed condition alongside the difference due to the increase in sea level rise.

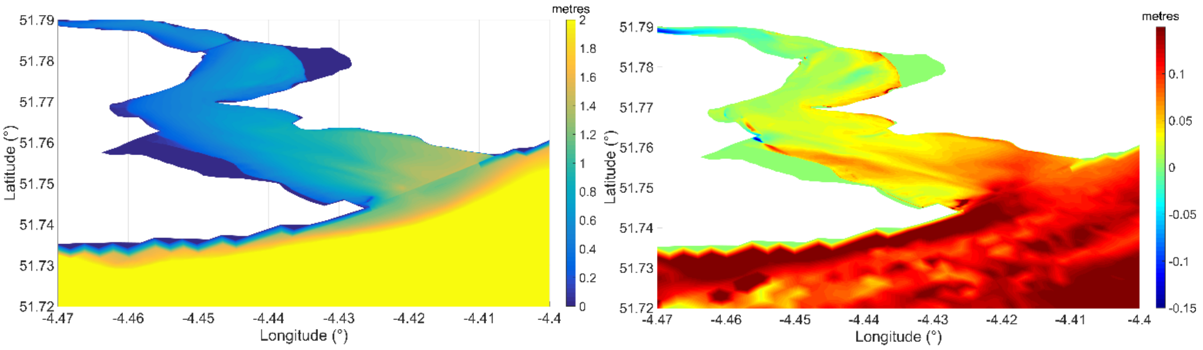

Figure 16 – Peak storm wave height under the 'present' grazed condition alongside the difference due to the increase in sea level rise.

In Figure 15, with extensive grazing, the increase in peak water depth across the Taf is noticeably different to the three other conditions. With the removal of vegetation, the increase due to sea level rise is greater than under the current (Figure 9) case, highlighting the drag effect of vegetation within Taf. Although this difference is noticeable, it is still a small magnitude change (~0.01m), and thus does not greatly influence coastal flooding within the estuary. Figure 16 shows that the impact of extensive grazing in future causes the wave height within the Taf to change less than that with vegetation (Figure 10). The difference between present and future is as with the other interventions, greatest outside of the estuary, however within the estuary the differences are largely between ~0.04-0.08m. When compared with the current configuration, the reduced attenuation effect of the vegetation is highlighted (Figure 10) due to the increased water level. While for the grazed case, the increase in water level only allows for a slight change in wave height.

Conclusions

Impact of coastal management interventions on future flooding of a small macro-tidal estuary is studied. The increase of extent, magnitude, and frequency of flooding due to the effects of climate change are a threat to both the built and natural environment. A wide array of approaches are being considered and investigated to counter this threat, with salt marshes considered as natural buffers for flooding. It was found that, other than the impacts of future climate change (sea level rise), the interventions themselves may have significant impacts on the estuarine hydrodynamic characteristics and morphology. The study provides insights into the role of sea level rise on the function of different management interventions during extreme storms.

The results highlight that the village of Laugharne within the Taf estuary will become increasingly vulnerable in future due to the impact of relative sea level rise. Of the three intervention scenarios the hard defence, which prevents onshore water and wave propagation, has the largest impact on future flooding of the village of Laugharne. Additionally, it has no influence on the wider hydrodynamic regime of the estuary compared to the current condition, although this option remains unpopular among local communities due to restricted access to the marsh and aesthetic issues. The implementation of the two managed realignment sites did not cause any large-scale change to the wider estuarine hydrodynamics, and also did not affect the water level at the boundary of the village of Laugharne. Therefore, the effect of managed realignment was limited to areas local to the two breach sites. The small increase in tidal prism of the estuary as a result of this scheme is an indicator for the lack of overall impact. The grazed case did cause widespread changes to the hydrodynamic behaviour of the Taf. However, it did not have a significant change on the water level and subsequent flooding, although it is important to consider the potential impact the change in hydrodynamics may have on estuary morphology. Whilst the link between the changes in hydrodynamics and changes in morphology is complex and nonlinear, the increase in wave heights across the marsh platforms prompts the potential to increase the vulnerability of the system to flooding.

The challenge of dealing with sea level rise remains a cause of increasing concern for future planning and management of coastal flooding. The results presented here highlight how sea level rise will impact on extreme storms, and subsequently coastal flooding for the small macrotidal Taf estuary. Identifying appropriate flood management solutions is complex and requires careful consideration of the short, and long-term effects.

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