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Desired and unintended impacts of managed realignment in a macrotidal estuary under present-day and future compound events.

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Abstract.

Increasing coastal risks and habitat losses have increased the interest in nature-based solutions for coastal protection. As such managed realignment (MR) is often presented as a win-win solution in rural areas. However, the level of coastal protection that MR can offer now and under climate change is still unclear. Evidence at the estuarine scale is scarce and existing studies rarely account for interactions between river discharge, tides and storm surge. We use a numerical model to assess estuarine-scale impacts of the Hesketh Out Marsh MR (UK) for storms scenarios under present and future sea level rise (SLR) conditions. Our scenarios were defined through repeated interactions with local actors and include river and ocean drivers combinations not previously explored. Results show that MR impacts are highly localised, spatially variable and storm dependent. The MR can reduce total water levels (TWL) upstream of the MR for storms on spring tides and reduce tidal range and surge. However, it can also have unintended consequences such as increasing inundation time opposite to the MR and raising TWL for storms on neap tides, low water levels (LWL) and river-induced water levels. SLR further amplifies these impacts by reducing TWL and increasing LWL as SLR increases. Our results suggest the MR ability to reduce water levels in estuaries may be overestimated when compound river-coastal extremes are not considered and underscores the need for comprehensive modelling and local engagement to achieve effective mitigation and adaptation at estuarine scale.

1 Introduction

Sea level rise (SLR) and extreme weather events are increasing the threat of flooding at the coast (Intergovernmental Panel on Climate Change (IPCC), 2023). With increasing urbanisation (Reimann et al., 2023) and increasing extreme sea levels (Jevrejeva et al., 2023), more and more people, property, infrastructure, and habitats are at risk at the coast (Reimann et al., 2023). This is particularly important for estuaries as they often are densily populated and they are hotspots for compound events with oceanic drivers occurring concomitantly or in close succession to river and pluvial drivers (Green et al., 2025; Lyddon et al., 2024; Robins et al., 2021; Couasnon et al., 2020; Bevacqua et al., 2020). Compound events have been shown to be particularly relevant in north and western Europe with storm events leading to combined river flooding, extreme precipitation and storm surge (Bevacqua et al., 2020; Couasnon et al., 2020; Hendry et al., 2019; Svensson and Jones, 2004; Robins et al., 2021). The meteorological drivers leading to compound events are projected to increase with climate change (Bevacqua et al., 2020) leading to increased intensity and frequency of coastal flooding (Xu et al., 2023).

Traditionally coasts and estuaries have been protected with hard engineered structures (e.g. concrete seawalls or dikes) that require unsustainable costs to keep up with SLR (Hinkel et al., 2014; Morris et al., 2020) and can contribute to land subsidence, coastal squeeze or habitat destruction (Temmerman et al., 2013). These unwanted side effects have favoured the shift towards nature-based solutions (NbS). NbS are defined by the IUCN as "solutions to societal challenges that involve working with nature" (Cohen-Shacham et al., 2016). Coastal and estuarine habitats and ecosystems (e.g. mangroves, saltmarh, oyster reefs) provide essential ecosystem services (Barbier et al., 2011) and can help mitigate the biodiversity-climate crises. However, they are under threat. Globally, saltmarsh losses are estimated at 0.28%/y (Campbell et al., 2022) between 2000-2019 and 50% of world saltmarshes have been lost (Barbier et al., 2011). In England the losses are more striking, with reported loss of 85% of the saltmarsh extent since the 1800s (EA, 2023). NbS schemes can fulfill objectives on climate adaptation such as environmental restoration and flood protection (O’Leary et al., 2023; Moraes et al., 2022; Seddon, 2022; Temmerman et al., 2013) and contribute to climate mitigation through blue carbon accumulation (Smeaton et al., 2024). In terms of coastal protection, NbS may be more cost-effective than engineered defences in the long term (van Zelst et al., 2021; Temmerman et al., 2013) since they can keep up with SLR under the right conditions (e.g. Schuerch et al., 2018; Kirwan et al., 2016). Due to the variability of coastal habitats and the relative novelty of NbS, the level of protection that NbS can provide is less well understood than that of hard engineered structures or natural habitats (Moraes et al., 2022; Morris et al., 2018; Pontee et al., 2016; Sutton-Grier et al., 2015; Bouma et al., 2014) and so NbS while emerging are not as widespread as traditional engineered defences (e.g. Morris et al., 2018; Temmerman et al., 2013).

Managed realignment (MR, also known as "depolderisation", "de-poldering", "set back", "rewetting" or "managed retreat", although the later can refer to planned relocation) is a popular NbS for coastal defence in Europe and particularly in the UK (ABPmer, 2024; Moraes et al., 2022). The Online Marine Registry (OMReg) database ABPmer (2024) indicates that over 80% of the coastal habitat creation and adaptation schemes in Europe are MR of which 63% are in the UK (as of January of 2026). The prevalence of this intervention is due to the double aim of MR: restoring intertidal habitats while managing flood and erosion risks in a more sustainable way (Esteves, 2013). MR consists of setting back the active line of defence and restoring intertidal habitats in the process (e.g. Esteves, 2013). The primary objective of most MR sites and other NbS is the recreation of intertidal habitats to compensate for habitat loss (Hudson et al., 2021), with the defence function only being a secondary benefit (Morris et al., 2018; Esteves, 2013; Dixon et al., 2008). In rural sparsely populated areas, restoring habitats can provide the justification to secure flood schemes to strengthen failing defences (MacDonald et al., 2020). As such, monitoring often focuses on ecological indicators (Esteves, 2012) and the analysis are often limited to the intervention site (Spencer and Harvey, 2012). However unexpected consequences of MR may extend beyond the intervention site and need consideration to avoid unsuitable solutions.

A growing number of studies look at the impact of MR at the system scale: Scheldt estuary (Belgium, SW Netherlands, Smolders et al. (2015)), Humber estuary (England, Townend and Pethick (2002)), Parret estuary (England, Pontee (2015)), estuaries in Wales (Fairchild et al., 2021), La Faute-sur-mer (France, Huguet et al. (2018)) or German Baltic sea (Kiesel et al., 2023). While MR has the potential to enhance coastal resilience, knowledge on the storm protection that MR can offer in estuaries (Fairchild et al., 2021) is still scarce and their effectiveness under climate change remains under-examined (Pontee, 2015; Seddon et al., 2020; Schuerch et al., 2022; Temmerman et al., 2023). Besides, MR studies often focus on extreme coastal events (i.e. surge, tide, waves) with limited available knowledge on the impact of MR under compound events due to both oceanic and fluvial drivers (cf. Pontee, 2015; Kiesel et al., 2019; Townend and Pethick, 2002). However the impact from river and sea in estuaries tends to worsen when extreme events at sea and on river occur at the same time or in close succession (Svensson and Jones, 2004; Bevacqua et al., 2020; Couasnon et al., 2020; Robins et al., 2021; Lyddon et al., 2024). Additionally, the evidence for the saltmarshes as coastal protection comes from large natural extensions (e.g. Temmerman et al., 2023; Leonardi et al., 2018; Wamsley et al., 2010) while MR sites in the UK have limited scale: 59% are smaller than 20ha and only 13% are larger than 100ha as of 2024 (ABPmer, 2024). These knowledge gaps lead to lack of evidence on the effectiveness of MR as a coastal defence. Combined with complex governance, financial barriers and limited social acceptance (van der Wal et al., 2002; Seddon et al., 2020; Apine and Stojanovic, 2026), this limits the uptake and implementation of MR. For example, in the UK, ambitions set out in national and local strategic policy documents are at risk of not being achieved under present rate of implementation (CCC, 2018).

To address these gaps, we investigate the changes in estuarine dynamics in response to compound events under current and future SLR following the implementation of a MR scheme. We consider the MR of Hesketh Out Marsh (HOM) in the Ribble estuary located in NW England, UK, where joint occurrences of high skew surge (i.e. the difference between the maximum observed sea level and the maximum predicted tide regardless of their timing during the tidal cycle) and high river discharge are common (Camus et al., 2021; Hendry et al., 2019). HOM is one of the largest MR schemes in the UK and Europe with a total surface of approximately 322ha of priority saltmarsh habitat (Fellows and Shirres, 2017). We explore the impacts of the MR at the estuary scale. We follow a community-informed approach and we design the study by taking into account local knowledge of those based and working in the area and who have influence and/or are affected and interested by the MR in HOM (i.e. local actors). The repeated interactions between scientists and local actors allowed the identification of common gaps in knowledge and the development of the scenarios considered in this study.

The remainder of the paper is structured as follows: the Ribble estuary and the MR site, the modelling system and the experimental design are described in Section 2. Section 3 compares the the MR scheme against the no intervention case for the storms considered while Section 4 considers those storms under future SLR scenarios. We discuss the results in Section 5 and provide our conclusions in Section 6.

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2 Methods and Data

2.1 The Ribble estuary and Hesketh Out Marsh (HOM)

HOM is located on the south bank of the Ribble estuary, a funnel shaped macrotidal, tidally dominated estuary in Liverpool Bay (NW England, Fig.1(a)). The ordinary tidal range in the estuary is 8.0m for spring tides and 4.0m for neap tides (UKHO, 2001). The intertidal saltmarsh habitat was privately reclaimed for farm use in the 1980s (van der Wal et al., 2002). This change was reverted with the creation of the MR; HOM West (HOMW, 180ha) was first developed in 2008 and later extended with HOM East (HOME, 160ha) in 2017. The MR was established through a partnership between the Environment Agency (EA), Natural England and the Royal Society for the Protecton of Birds (RSPB) as a compensation scheme for habitat loss elsewhere (Tovey et al., 2009). HOM contributes to habitat creation objectives elsewhere in Northwest England under the Department for Environment, Food and Rural Affairs' (DEFRA) biodiversity 2020 strategy (DEFRA, 2012), and helps the UK comply with Habitats Directive and the Wild Birds Directive (now Habitat Regulations) and meet the Water Framework Directive (now Water Environment) objectives (Fellows and Shirres, 2017). The creation of the saltmarsh habitat was required to secure the funding for the repairs of the failing inner wall (MacDonald et al., 2020). The site provides several ecosystem services: flood protection (1 in 200 year standard flood protection to 143 residential properties, 3 commercial buildings and 300ha of prime agricultural land), natural reserve, recreational amenity and climate change mitigation through carbon sequestration.

To explore the impacts of MR in HOM at the estuarine scale, we consider the bathymetry and saltmarsh extent prior to the development of the MR and that of present day with the MR in place (Fig. 1(b)-(c)). Prior to MR the site was low-lying land almost completely surrounded by embankments with crest levels varying 7-7.5m Above Ordnance Datum Newlyn (AODN) (Tovey et al., 2009; Pontee, 2005). The MR works included the recreation of historic creeks and lagoons, the breaching of the outer embankment and the reinforcement of earth embankments with local materials so they reach 7.7m AODN (ClimateADAPT, 2025). The saltmarsh has an average height of 3.5m above mean sea level. Fig. 1(f)) shows the direct impact of the MR on the bathymetry (i.e. reinforced embankments in dark red, breaches and creeks in dark blue, and the larger accretion on HOMW than in HOME with darker shade of red on the west than on the east of the MR site).

2.2 The numerical model - model set up

We used a two dimensional barotropic implementation of the finite difference hydrodynamic model Delft3D-FLOW (Lesser et al., 2004). The model calculates non-steady flow using Navier-Stokes equations and computes the barotropic tide-surge-river propagation across the domain. The vegetation module in Delft3D integrates the 3D influence of the vegetation stems as an additional source term for friction into the momentum equation. The vegetation is considered as vertical rigid cylinders following the formulation of Baptist et al. (2007). For a more detailed description of the vegetation module we refer the reader to DELFT Hydraulics (2014).

The model domain, computational grid and bathymetries of this study are shown in Fig. 1. The domain set-up, calibration and validation of the model of this study were originally performed by Li et al. (2019, 2018) to which we refer the reader

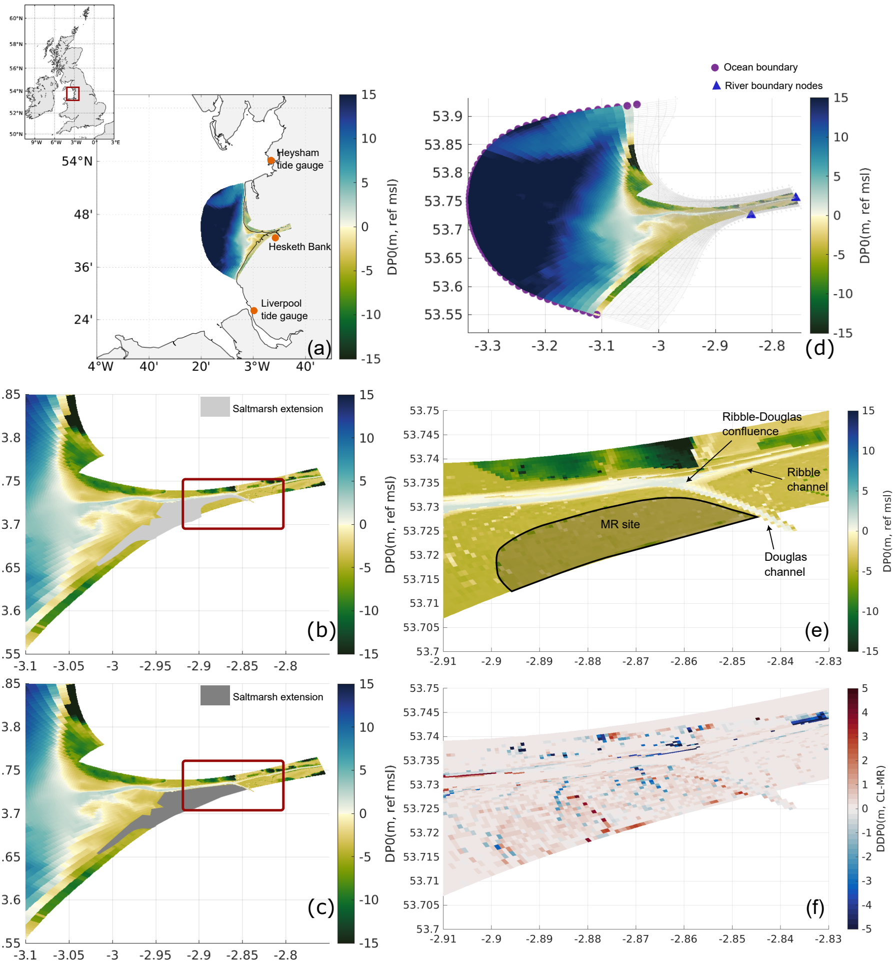

Figure 1. Ribble estuary model: (a) Location of the Ribble estuary, red rectangle indicates the location in the UK. Orange dots indicate the location of Liverpool and Heysham tide gauges that recorded extreme events in the region and of the village of Hesketh Bank. Zoom on the model domain prior (b) and after (c) MR; the colourbar indicates bathymetry with blue and green tones indicating below and above mean sea level values respectively. The red rectangle depicts the zoom in the Hesketh Out Marsh site presented in (e) and (f). The shaded grey area delimit the saltmarsh extent considered in each case. (d) Full model domain and boundary nodes, purple and blue nodes represent respectively the ocean open boundary and the river discharge boundary nodes. (e) Zoom in the Hesketh Out Marsh site prior to the MR, the colourbar indicates bathymetry. The black line delimits the MR site. (f) Difference between the baseline 2006 bathymetry before intervention and the 2022 bathymetry once the intervention was completed. Red and blue indicate higher and lower bedlevel with respect to the original bathymetry.

for details. The model has also been used to explore saltmarsh resilience (Pannozzo et al., 2022, 2021). The domain has a fan shape and consists of a curvilinear grid of 344x80 cells in the east-west and north-south directions respectively. The grid resolution is maximum within the river with a resolution of ∼20m and decreases seaward with ∼70m across the intertidal areas

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and ∼300m offshore. The bathymetry was obtained from the combination of two datasets 1) 1 Arcsec resolution bathymetric data downloaded from EDINA Digimap for the open sea regions and 2) a 2m resolution DTM LiDAR data downloaded from the Environment Agency's LiDAR repository for the coastal regions. We applied spatially varying Vertical Offshore Reference Frame corrections provided by the UK Hydrographic Office to adjust both datasets to mean sea level (msl). We use the same bathymetry as Li et al. (2018) for the simulations prior to the MR. This bathymetry is merged with a 2022 AD bathymetry from EDINA DIGIMAP and topography from EA LiDAR repository that incorporates the changes of the MR for the simulations once the MR is implemented. The simulations prior and after MR also include the changes in the saltmarsh extent (i.e. the area where we consider that there is vegetation (Fig. 1(b) and Fig. 1(c), notice that in both cases there is a natural saltmarsh downstream of the MR site). We considered a fully vegetated marsh with a density of 512 stems/m2, a plant height of 0.9m and a stem diametre of 0.008m following Li et al. (2018) and (Pannozzo et al., 2021). We do not account for spatially and temporally varying vegetation due to the lack of available detailed information on plant-specific characteristics. While the parameterisation we use may affect qualitatively our results and may be a source of uncertainty (e.g. van Rooijen et al., 2016; Temmerman et al., 2023), it should not affect the qualitative trends we obtain and our interpretation of results.

The model is forced with external tide and surge levels and river discharge. Given the small size of the domain, it will experience limited internal surge generation (Brown et al., 2011) and so local meteorological forcing is not considered. The estuary experiences moderate waves (Pye and Neal, 1994) and for the purpose of this study they are not considered. The model has three open lateral boundaries: one 20km offshore to minimise potential boundary effects (purple dots in Fig.1d) and two other to include the primary sources of fresh water: one to the south across the river Douglas and one to the east across the river Ribble (blue triangles in Fig.1(d)). Data for the west ocean boundary was provided by the Atlantic Margin Model 7km (AMM7, regional North West European Shelf) ERA5-forced hindcast run of the NEMO-surge and tide model ran at the MetOffice (Williams et al., 2024; Furner et al., 2016). NEMO-surge and tide model is a 2D barotropic configuration of the NEMO model. It covers the North West European shelf with a horizontal resolution of approximately 7km and provides 15-minute time series of water elevation at grid points that were interpolated into the Delft3D boundary points. The Ribble River is a benchmark catchment with very little human intervention and considered near-natural with relatively quick response to precipitation (Harrigan et al., 2018). Given that it is a fast catchment, it is crucial to consider high resolution river data to properly account for the maximum river discharge at the correct timing (Robins et al., 2021). Quality controlled 15-minute river flow data were obtained from the Environment Agency. We used the station Ribble at Samlesbury (713019), Darwen at Blue Bridge (713122), Yarrow at Croston Mill (700408), Douglas at Wanes Blades Bridge (700306). Unfortunately, the other station in the area for the Lockstock at Littlewood Bridge (700509) had no available data for the periods of interest. Daily means at this station represent 16.39% of the river discharge for the Douglas-Yarrow and only 2.67% of the river discharge for the whole Ribble catchment (NRFA, 2025a). We aggregated the flows to form two time series of total discharge: one for the Ribble-Darwen (east boundary condition) and one for the Douglas-Yarrow (south open boundary condition). The model is started from rest with null velocities and uniform mean water level and spins up for a couple of days. To be able to study the impact of the MR in tidal dynamics we run the model for a month.

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2.3 Scenario development and community-informed research

We tailored the experimental design through a series of participatory workshops by considering the coupled human-environment estuarine system and incorporating the needs and concerns of local actors (i.e. local councillors, representatives of government agencies, nature conservation charities, and local landowners and farmers working in the area). We summarised outcomes from site visits, fuzzy cognitive mapping, focus groups, and scenario design workshops (Apine and Stojanovic, 2026; Meschini and Apine, 2025; Meschini and Robinson, 2024) into knowledge needs and modelling scenarios to explore. Local actors also provided feedback on preliminary results. The storm scenarios build on recent historic events with strong local narrative and legacy, and that had a lasting impact in local actors: storm Xaver 3-6 December 2013, Desmond 5-6 December 2015 and Ciara 8–9 February 2020 (Fig. 2).

Storm Xaver (Fig. 2(a1)-(d1)) has been reported as the worst coastal flooding event since the storm of 1953 (Haigh et al., 2017). The storm developed off the coast of Greenland and moved eastward towards the UK. The combination of northwesterly winds and high spring tides caused extreme high water levels in the west of UK with a record breaking peak total water level of 11.148m in Liverpool, the largest recorded for 1993-2022 in Liverpool (BODC, 2025). A skew surge of 1.08m was recorded in Liverpool (Haigh et al., 2017; Wadey et al., 2015). Storm Desmond (Fig. 2(a2)-(d2)) caused compound flooding across the west coast of Great Britan (Matthews et al., 2018) due to the combination of heavy rain, high river discharges of 750m^3/s at Ribble Samlesbury (NRFA, 2025b) where the median annual maxima flood (annual exceedance probability of 0.5 and a return period of 2 years) has a value of 601m^3/s and incoming tide and was a near-miss overtopping event for the inner embankment in HOM (local actors, personal communication). Storm Ciara (Fig. 2(a3)-(d3)) brought high winds and intense rainfall of over 65mm in 18h in the Ribble catchment (MetOffice, 2020) that translated into record breaking discharges with the largest ever recorded river discharge at Ribble Samlesbury station with 1171.3m^3/s (NRFA, 2025b). Storm Ciara was concomitant with spring tides and caused extreme water levels; the recorded skew surge at Heysham was 1.02m (BODC, 2025).

We analyse the impact that the MR vs. no intervention has at the estuarine system scale by running the simulations with and without MR (i.e. simulations with MR include changes both in bathymetry and vegetation). We explore the three storms considered while also isolating the impact associated with each driver (i.e. surge, river and tide). We focus our analysis on the four days around each storm, starting 12h before the storm arrival (Fig. 2). For each storm we ran four simulations (cf. Table 1): T (tide-only), TS (tide-surge, no river), TR (tide-river, no surge) and F (fully-forced, i.e. tide-surge-river). We combine these simulations to isolate the contribution of different drivers on the estuarine dynamics (cf. Table 2). The fully-forced simulations (Fully, F) allow assessment of the MR impacts on the dynamics of the estuary under compound event. The tide-only (T) experiments allow the study of the impact of the MR on the tide. The influence on the surge dynamics (i.e. S in Table 2) including non-linear interactions tide-surge and river-surge can be calculated from the difference between the fully-forced (Fully) and the tide-river (TR) forced simulations. The difference between the fully-forced (Fully) and the tide-surge (TS) simulations provides the impact of the MR due to the river-induce dynamics (i.e. R in Table 2) including non-linear tide-river and river-surge interactions.

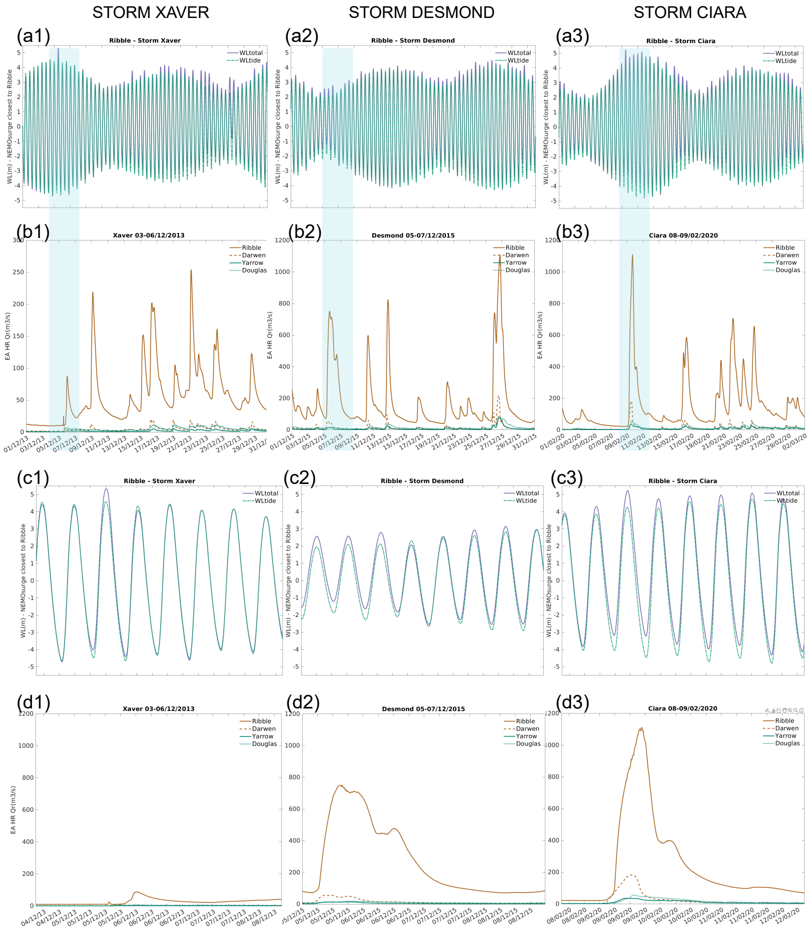

Figure 2. Storms considered: Xaver (1st column), Desmond (2nd column), Ciara (3rd column), (a1)-(a3) total water level (purple) and tide (green) from NEMOsurge model at the closest node to the Ribble estuary for the three storms considered and the period modelled. (b1)-(b3) River discharge at the Ribble at Salemsbury (713019), Darwen at Blue Bridge (713122), Yarrow at Croston Mill (700408) and Douglas at Wanes Blades Bridge (700306) river gauges for the three storms. The pale blue rectangle highlights the storm duration over which this study focuses. (c1)-(c3) Total water level and tide, zoom over the analysis period. (d1)-(d3) River discharge, zoom over the analysis period.

We further evaluate the impact of the MR under future SLR for the different storms considered. This impact is calculated as the difference between the estuarine dynamics without MR under future SLR and estuarine dynamics with MR under future SLR (i.e. noMR (SLR) - MR (SLR)). The future SLR is imposed along the ocean open boundary by adding it to the water levels from the AMM7 NEMO model. This way the SLR propagates dynamically through the domain guided by the model equations. We consider four future sea level scenarios: 0.24m, 0.35m, 0.67cm and 1.02m. These correspond to the median and 95th percentile by 2050 and 2100 of the regional projections for the High-end Representative Concentration Pathway 8.5 (RCP8.5) future climate scenario from UK Climate Projections (UKCP18, Palmer et al. (2018, 2024); Lowe et al. (2018)) that assumes business as usual. The applicability of our results is broader than the response to a specific future climate scenario

Table 1. Simulations performed for each storm under present climate. Only the fully forced simulation is also performed under four sea level rise scenarios.

Simulations

	Forcing				
Name	Tide	Surge	River	SLR	Drivers and interactions
Tide only (T)	X				$Tide$
Tide-surge (TS)	X	X			Tide + Surge + TideSurge
Tide-river (TR)	X		X		Tide + River + TideRiver
Fully-forced (F)	X	X	X		Tide + River + Surge + TideRiver + TideSurge + RiverSurge + TideRiverSurge
Fully-forced SLR (FSLR)	X	X	X	X	As for F + SLR + SLR non-linear Interactions

Table 2. Analysis performed for each storm considered. The fully-forced storms are considered under four different sea level rise scenarios.

Analysis

Name	Simulations	Contributions
T	$Tide$	Tide
S	$Fully - TR$	Surge + TideSurge + RiverSurge
R	$Fully - TS$	River + TideRiver + RiverSurge
F	$Fully$	Tide + River + Surge + TideRiver + TideSurge + RiverSurge + TideSurgeRiver
FSLR	$FullySLR$	As for F + SLR + SLR non-linear Interactions

since specific values of SLR correspond to different time horizons under different climate scenarios and/or likelihood. For example 0.24m is the median RCP8.5 SLR in 2050 and the 90% percentile RCP8.5 SLR in 2040 while 0.67m is the median RCP8.5 SLR in 2100 and also the 95% percentile in 2075 (Lowe et al., 2018).

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3 Results: Impacts of MR at estuarine scale nowadays

3.1 Impact of MR on estuarine dynamics under compound events

Maximum inundation time (i.e. duration of time for which a given cell is covered in water during the simulated period), inundation area (i.e. extent that is covered in water at any time of the simulated period), maximum total water levels (TWL) and current speed for each storm with and without MR are shown in Fig. 3. The MR modifies the dynamics in the wider estuary although little impact of the MR is observed offshore (not shown). For the three storms, the MR reduces the inundation time over the MR site while increasing it opposite to the MR site (Fig. 3 (b1)-(b3)). For storm Xaver, the inundation time changes are mostly limited to the MR site, with reductions of about 30h if the MR is in place. For storm Desmond, the inundation time displays reductions of about 80h over the MR site and increases of the same order of magnitude occur opposite to the MR site. For storm Ciara inundation time is reduced by 15 to 18h over the MR and increases of the same order of magnitude occur opposite to the MR site. The inundated area remain the same for storms happening at spring tides (i.e. Xaver and Ciara, Fig. 3(d1), Fig. 3(d3) and Fig. A1). For Desmond, happening at neap tides, the MR changes the inundated area, reducing it in the MR site itself while increasing it opposite to the MR (Fig. 3(b2), Fig. 3(d2) and Fig. A1).

For both storms happening at spring tides (i.e. Xaver and Ciara), the MR increases TWL in the downstream of the MR site while reducing TWL upstream of it. For both Xaver and Ciara, the MR increases TWL in HOMW (i.e. western side of the MR), in the vicinity and along the drainage channel to the west of the MR site by 0.2m-0.3m. Further downstream, our model indicates increases of 0.2m in TWL during Xaver and reductions of 0.1m in TWL for storm Ciara. The MR reduces TWL by 0.10-0.15m in HOME and the upstream region of the estuary (Fig. 3 (d1) and (d3)). For storm Desmond, changes in TWL due to the MR are localised on the main channels with increases of 0.2m and similar reductions limited to the most upstream reach of the river Ribble (Fig. 3 (d2)). The very dark points in Fig. 3(d1) and Fig. 3(d3) correspond to points that remain dry when the MR is in place.

The changes in current speeds due to the MR show fine scale spatial variability reflecting the presence of tidal channels and creeks and vegetation blockages that redistribute water towards other areas. During storms Xaver and Ciara, currents generally intensify along the MR creeks and channels and weaken along the marsh extent downstream the MR site and opposite to the MR site by 0.6-0.8m/s (Fig. 3(f1) and Fig. 3(f3)). For storm Desmond, current speeds slow down by 0.3-0.4m/s at the confluence of the river Ribble and Douglas, conversely there is an intensification by 0.3-0.4m/s both upstream and downstream of it when the MR is in place (Fig. 3(f2)). These changes in maximum current speed impact on the time of the maximum TWL for each of the storms (Fig. A2). For storm Xaver, the MR hastens the arrival of TWL over the saltmarsh area downstream of the MR site but delays TWL by several hours opposite to the MR and by 30-60’ over the MR itself and the most offshore part of the estuary (Fig. A2(c1)-(d1)). For storm Desmond, the MR delays TWL offshore maximum TWL while hastening TWL in the upper Ribble channel (Fig A2(c2)-(d2)). For storm Ciara, the MR delays TWL by 30’ over the saltmarsh downstream the MR site and the MR site itself and by several hours at the confluence of the rivers Ribble and Douglas (Fig. A2(c3)-(d3)).

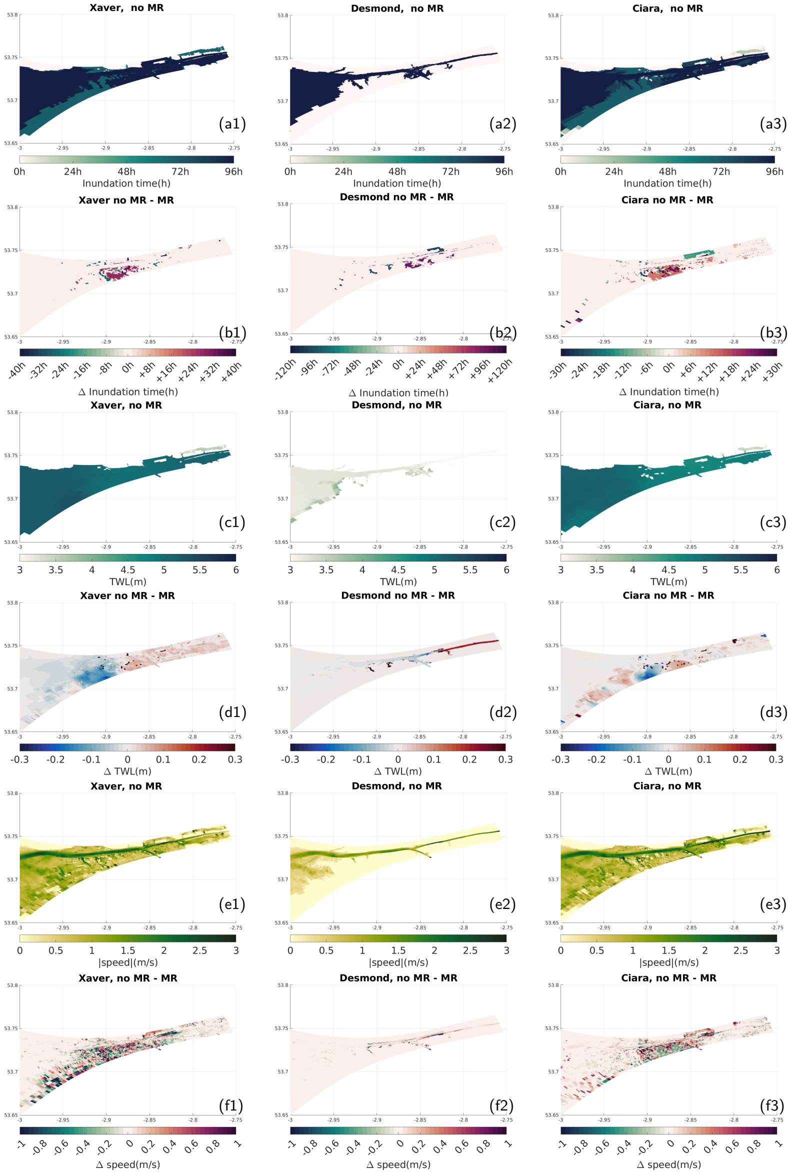

Figure 3. Changes in inundation time, maximum Total Water Levels (TWL), and maximum current speed due to the managed realignment for the storms considered from left to right Xaver, Desmond and Ciara. (a1)-(a3) inundation time prior to the MR. (b1)-(b3) Change in inundation time when the MR is in place. (c1)-(c3) Maximum TWL prior to the MR. (d1)-(d3) Change in the maximum TWL due to the MR. (e1)-(e3) Maximum current speed prior to the MR. (f1)-(f3) Change in maximum current speed due to the MR. Red and burgundy shades indicate decrease due to the MR while blue and green shades indicate increase due to the MR.

We consider the period extending 2h before and 4h after low tide at the mouth to calculate the highest low water levels (LWL). This way we account for the distortion of the tide in the estuary. For storm Xaver, the MR lowers LWL along the main channel

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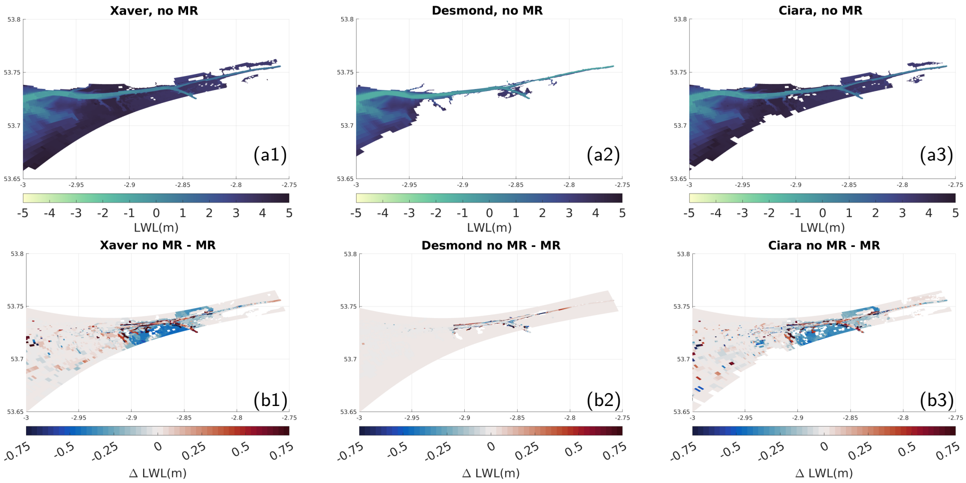

Figure 4. Changes in the highest low water levels (LWL) due to the managed realignment (MR) for the storms considered (Xaver 1st column, Desmond 2nd column and Ciara 3rd column). (a1)-(a3) LWL prior to MR. (b1)-(b3) change in LWL when the MR is in place. Red and blue shades respectively indicate decrease and increase due to the MR.

in the vicinity of the MR site, the MR creeks and confluence of river Douglas and Ribble in the order of 0.75m to 1.1m while rising LWL on the MR and upstream opposite to the MR by 0.5m-0.75m (Fig. 4b1). For storm Desmond, impacts on LWL are localised along the main channel in the vicinity of the MR site and the confluence of the river Ribble and the river Douglas with increases of 0.5-1.0m (Fig. 4b2). For storm Ciara, the MR raises LWL by 0.25m-0.75m over the MR site, opposite to the MR itself and upstream the confluence of the Ribble and Douglas while reducing LWL along the main channel by 0.5m (Fig. 4(b3)). The MR hastens LWL for storm Xaver over the MR site and opposite to it while delaying LWL elsewhere (Fig. A4(c1)). For storm Desmond and storm Ciara, the MR delays LWL (Fig. A4(c2)-(c3)).

3.2 Impact on tide dynamics due to MR

The MR can modify the tidal dynamics of the estuary in terms of spring tidal range (STR) and mean higher high water (MHHW). STR is defined as twice the sum of the M2 and S2 amplitudes, while MHHW is defined as the sum of M2, O1 and K1. The influence of the MR is constrained to the vicinity of the MR site. The MR reduces STR by about 0.2m-0.3m over the MR site and opposite to it while increasing STR by about 0.8m in the vicinity of the main channel and along the new creeks developed as part of the MR (Fig. 5(c1)-(d1)). Changes in MHHW due to the MR remain localised in the vicinity of the MR site with decreases by 0.1-0.2m on the MR site and opposite to it and increases by 0.4-0.6m along the new creeks (Fig. 5(c2)-(d2)).

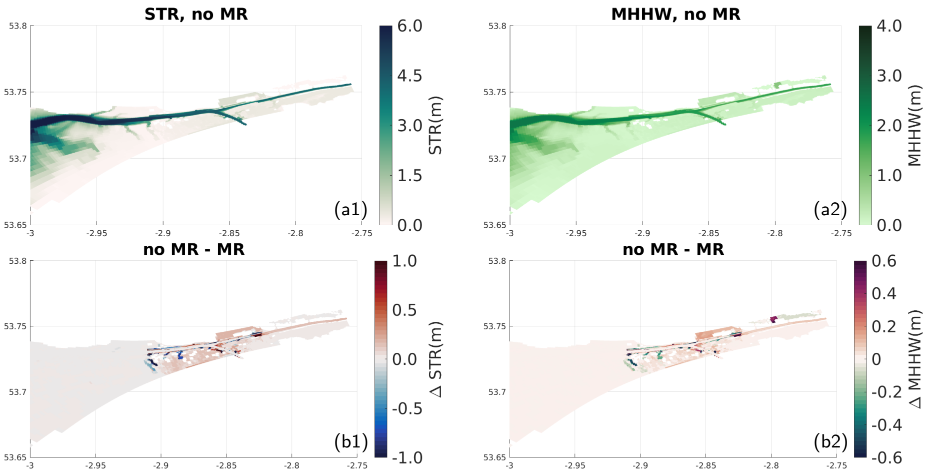

Figure 5. Changes in tidal amplitudes due to the managed realignment (MR). (a1) Spring Tidal Range (STR) prior to managed realignment. (b1) STR when the MR is in place. (c1) Change in the STR due to the MR. The grey rectangle depicts the area zoomed in (d1). (a2) Mean Higher High Water (MHHW) prior to MR. (b2) MHHW when the MR is in place. (c2) Change in the MHHW when the MR is in place. The grey rectangle depicts the area zoomed in (d2). Red and burgundy indicate decrease due to the MR, conversely blue and green indicate increase due to the MR.

3.3 Impact on surge dynamics due to MR

We examine the impact of the MR in the propagation of the surge (S in Table 2) for the three storms considered. Fig. 6 (a1)-(a3) shows the maximum surge in the Ribble estuary without MR. Storm Xaver presents surge values in the region of 1-1.1m with values reaching 1.2m at the confluence of the river Douglas and the river Ribble (Fig. 6(a1)). These values compare well with the skew surge of 1.08m recorded in Liverpool (Haigh et al., 2017). Conversely storm Desmond presents negligible values of maximum surge beyond the main channel since the storm ocurred during neap tides (Fig. 6(a2)). Storm Ciara presents the largest surge with values over 1.6m along the main channel and northern flank of the estuary when the MR is not in place (Fig. 6(a3)). The higher surge value than that of the 1.02m skew surge recorded in Heysham (BODC, 2025) reflects the amplification of surge and tide in funnel-shaped estuaries.

We observe a reduction of 0.1-0.2m in the surge upstream and in the vicinity of the confluence of the rivers Ribble and Douglas if the MR is in place and increases in surge over the MR site once the MR is in place (Fig. 6 (b1)-(b3)). For storm Xaver, the MR increases the surge offshore of the MR by 0.2m and by up to 0.3m-0.4m in the MR site while decreasing it upstream of the rivers' confluence by 0.1m-0.2m (Fig. 6(b1)). For storm Desmond, the MR impact is localised in the main channel with increases by up to 0.5m along the MR creeks and decreases it by 0.1-0.2m in the confluence of the rivers Ribble and Douglas (Fig. 6(b2)). For Storm Ciara, the MR increases surge by 0.4m-0.5m over the MR site while decreasing it opposite to the MR site by about 0.5m and by 0.1-0.2m upstream of the rivers' confluence (Fig. 6(b3)). The darkest red colour points on the MR

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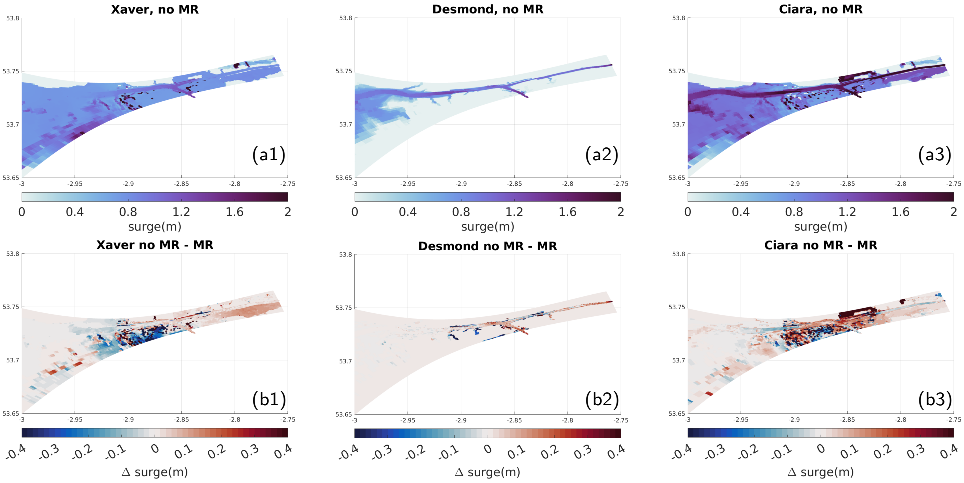

Figure 6. Changes in surge due to the MR for the three storms considered from left to right Xaver, Desmond and Ciara. (a1)-(a3) Maximum surge prior to MR. (b1)-(b3) Change in maximum surge when the MR is in place. Red shades indicate decrease due to the MR, conversely blue shades indicate increase due to the MR.

site for both Xaver and Ciara correspond to points that are covered with water when the MR is not in place but remain dry when the MR is in place.

The MR impacts the timing of the maximum surge (Fig. A6). For storm Xaver, the MR hastens the arrival of maximum surge over the MR site by about 1h while delaying it by about 1h in the offshore part of the estuary and by several hours in the upstream part of the estuary opposite to the MR site (Fig. A6(c1)). For storm Desmond, the MR delays the arrival of surges by over 10h in the most upstream channel (Fig. A6(c2)). For storm Ciara, the MR delays the surge over the MR sie by about 2h, while hastening surges along the main channel by about 4h and opposite to the MR by over 10h (Fig. A6(c3)).

3.4 Impact on river-induced dynamics due to MR

We examine the impact of the MR in river-induced water levels (R in Table 2, Fig. 7 and A7). Prior to the MR, for both storm Xaver and storm Ciara, river-induced water levels are maximum on the future MR site and offshore of it, particularly along the drainage channel west off it. Maximum values are in the order of 0.3m and up to 0.7m in some creeks for Xaver (Fig. 7a1) and in the order of 0.4m and up to 0.8m in some creeks for Ciara (Fig. 7a3). Conversely, storm Desmond only generates river-induced water levels in the vicinity of the future MR site with values of 0.3m along the Ribble channel and values of 0.4m along the Douglas channel (Fig. 7a2)).

Overall the MR increases river-induced water levels in the vicinity of the MR and in the MR itself (R in Table 2, Fig. 7 and Fig. A7). For storm Xaver, the MR increases water levels by 0.5m to the west of the MR and by 0.2m-0.4m over the MR site, while reducing levels along the MR creeks by 0.5m (Fig. 7(b1) and Fig. A7(b1)-(c1)). For storm Desmond the MR increases river-induced water levels along the main channels of the river Douglas and river Ribble by up to 0.2m (Fig. 7(b2)). For storm

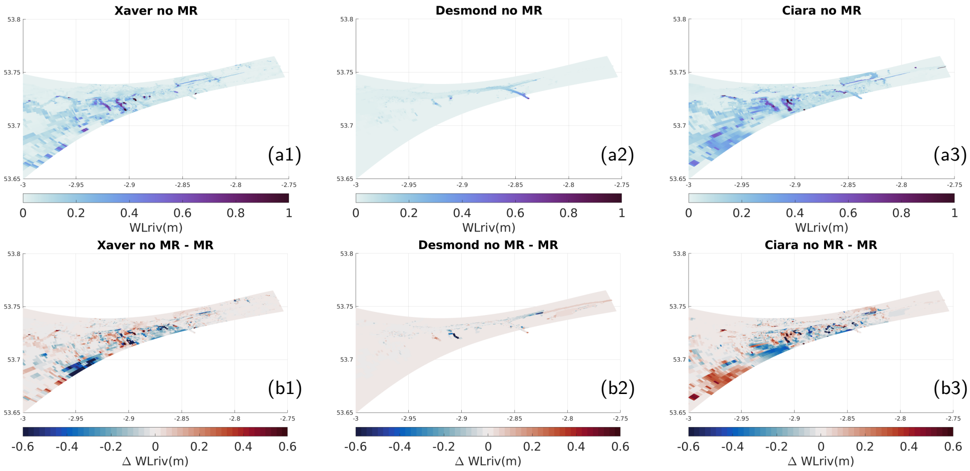

Figure 7. Changes in river-induced WL due to the MR for storms Xaver, Desmond, Ciara. (a1)-(a3) Maximum river-induced water level prior to MR. (b1)-(b3) Change in maximum river-induced water level when the MR is in place. Red shades indicate decrease due to the MR, conversely blue shades indicate increase due to the MR.

Ciara, the MR decreases river-induced water levels by about 0.3m over the saltmarsh platform to the west of the MR while decreasing them by about 0.2m on the MR site (Fig. 7(b3)).

The impact of the MR on the time of the maximum river-induced water levels (Fig. A8) presents a more complex pattern than for TWL (3.1) or surge (3.3). For storm Xaver, the MR generally delays the maximum river-induced water levels except at the confluence of the Ribble and Douglas (Fig. A8(c1)). For storm Desmond, the MR delays the arrival of maximum river-induced WL along the river Ribble and river Douglas (Fig. A8(c2)). For storm Ciara, the MR delays maximum river-induced water levels over most of the estuary, but hastens them opposite to the MR site A8(c3)).

4 Results: Impact of MR on estuarine dynamics under rising sea levels

The impact of the MR on the inundation time under SLR is localised over the MR site and upstream of it (Fig. 8). For both storm Xaver and Ciara we observe the largest impact for the lowest SLR (i.e. SLR =0.24m) with the MR reducing the inundation time by 26h for storm Xaver (Fig. 8(a1)) and 21h for storm Ciara (Fig. 8(a3)). For the largest SLR (i.e. 1.02m), the impact of the MR on the inundation time is limited to fewer points for both storm Xaver and Ciara (Fig. 8(d1) and Fig. 8(d3)). For storm Desmond, the impact of the MR on the inundation time increases as the SLR increases with maximum reductions in the inundation time for SLR=0.67m in the order of 40h over the natural marsh and increases of over 40h on the northern flank of the estuary (Fig. 8(a2)-(c2)). Similarly to storm Xaver and storm Ciara, the impact of the MR on the inundation time for storm Desmond is limited to fewer points for the largest SLR evaluated (i.e. SLR = 1.02m, Fig. 8(d2)).

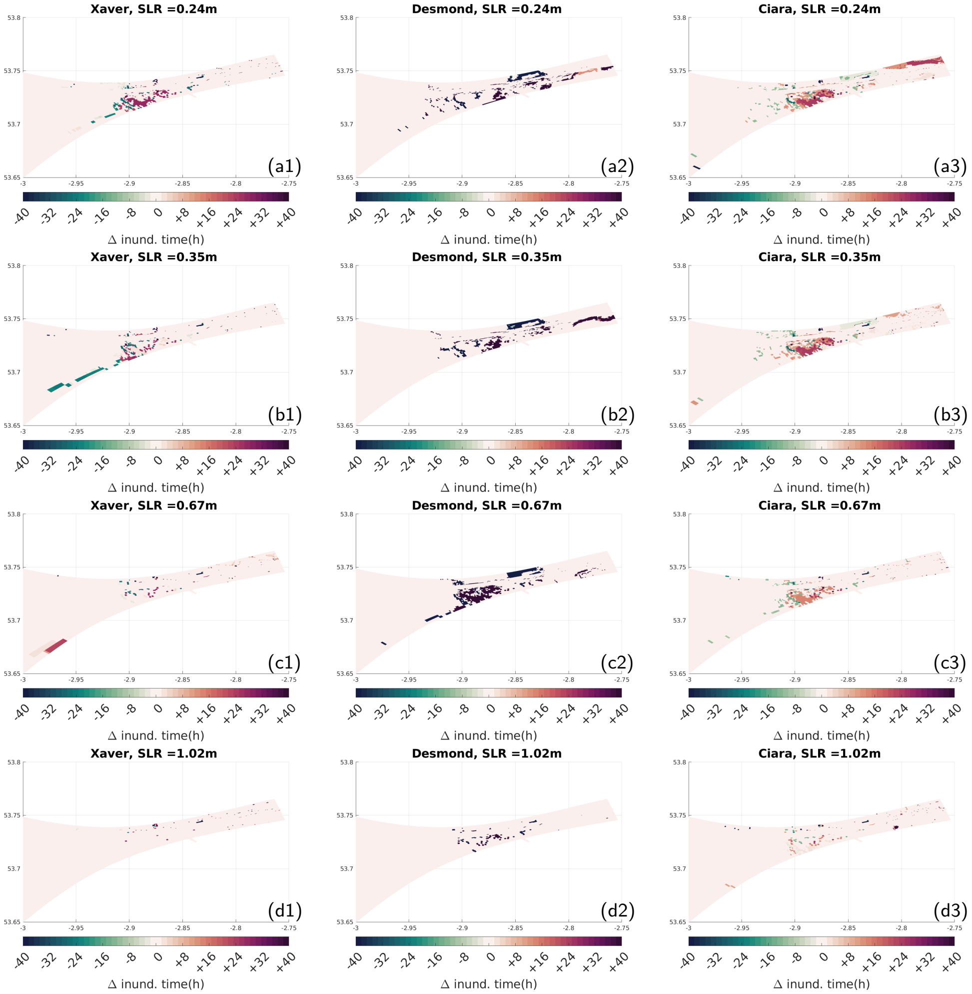

Figure 8. Changes in inundation time due to the MR for storms Xaver, Desmond, Ciara under the four different sea level rise (SLR) considered calculated as no MR (SLR) - MR (SLR). (a1)-(a3) Under SLR=0.24m. (b1)-(b3) Under SLR=0.35m. (c1)-(c3) Under SLR=0.67m. (d1)-(d3) Under SLR=1.02m. Red and blue indicate decrease and increase due to MR respectively.

In terms of maximum TWL under SLR (Fig. 9), the impact of the MR is most noticeable on the vicinity of the MR site and upstream of the MR site. The MR increases maximum TWL over the saltmarsh and over HOMW by about 0.1m for storm Xaver and 0.25m for storm Ciara while reducing TWL over HOME and the upstream part of the estuary by up to 0.20m for storm Xaver and 0.15m for storm Ciara (Fig. 9(a1)-(c1) and Fig. 9(a3)-(c3)). As the SLR increases, the MR slightly increases TWL by 0.10-0.15m over the saltmarh offshore the MR site while decreasing maximum TWL over the whole MR and upstream of it by up to 0.3m for the maximum SLR analysed (i.e. SLR = 1.02m, Fig. 9(d1) and Fig. 9(d3)). For storm Desmond, the

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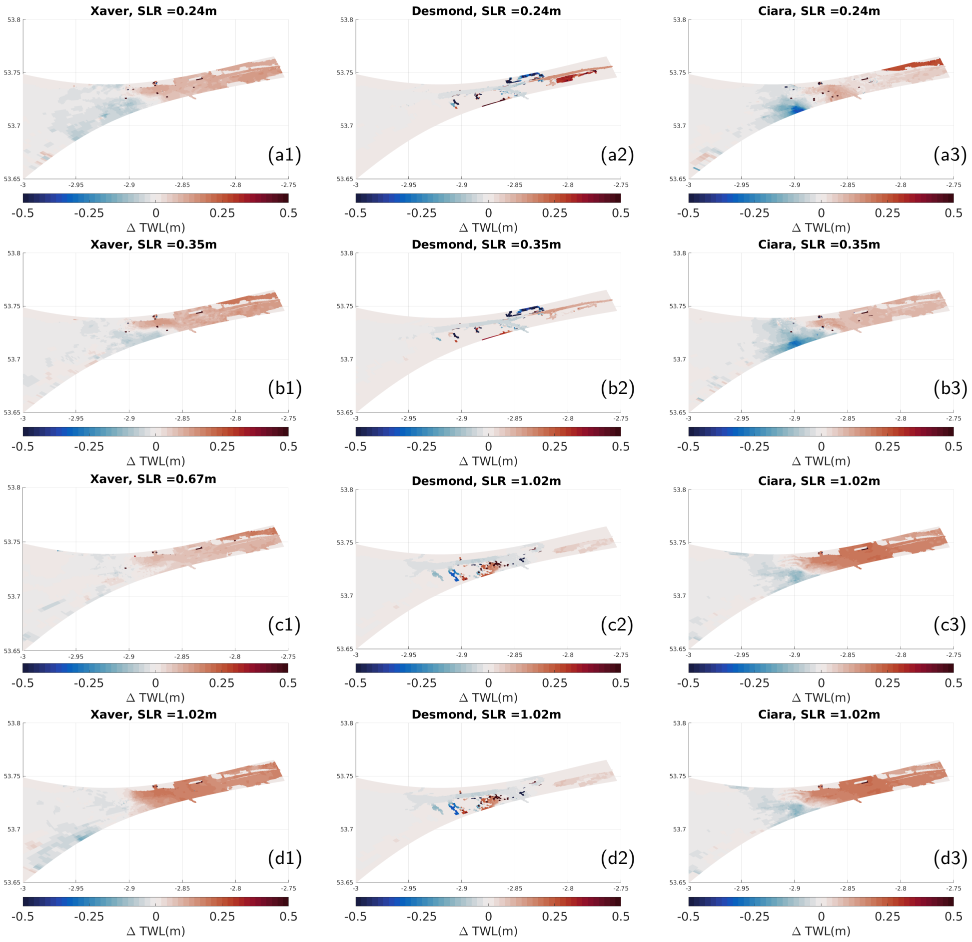

Figure 9. Changes in maximum TWL due to the MR for Xaver, Desmond, Ciara under the different sea level rise (SLR) considered. (a1)-(a3) Under SLR=0.24m. (b1)-(b3) Under SLR=0.35m. (c1)-(c3) Under SLR=0.67m. (d1)-(d3) Under SLR=1.02m. Red shades indicate decrease due to the MR, conversely blue shades indicate increase due to the MR.

MR increases TWL by about 0.1m in the main Ribble and Douglas channel, 0.3m along the new creeks and up to 0.4m on the opposite flank of the estuary. These largest increases are observed for SLR = 0.67m (Fig. 9(c2))

For storm Xaver, the MR generally intensifies current speeds along the creeks in the MR site while reducing them elsewhere on the MR site and opposite to it (Fig. 10(a1)-(d1)). For the lowest SLR, the MR decreases current speeds along the main channel up to the confluence with the Douglas from where currents are increased. This pattern is reversed for the highest SLR for which current speeds are increased along the main channel before the confluence while decreasing upstream of it (Fig. 10(d1)). For storm Desmond, the MR hastens current speeds by 0.6m/s along the main Ribble channel, MR creeks and opposite to the MR site while slowing currents by up to 0.6m/s along the Douglas channel for the two lowest SLR (Fig. 10(a2)-(b2)) .

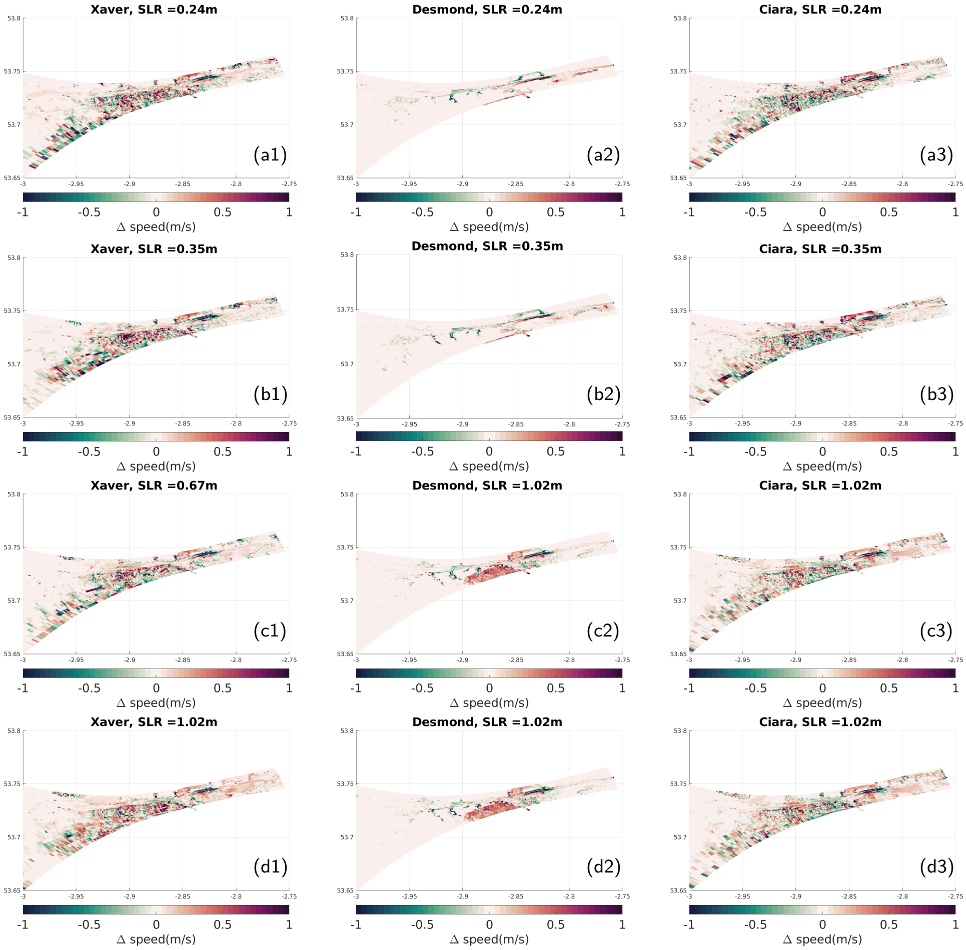

Figure 10. Changes in maximum current speed due to the managed realignment for the storms considered Xaver, Desmond and Ciara under the different sea level rise (SLR) considered. (a1)-(a3) Under SLR = 0.24m. (b1)-(b3) Under SLR = 0.35m. (c1)-(c3) Under SLR = 0.67m. (d1)-(d3) Under SLR = 1.02m. Red and blue indicate respectively decrease and increase due to MR.

As SLR increases, the MR impact on currents extends over the MR site and opposite to it, with reductions in the order of 0.6m/s, conversely along the main Ribble channel currents are hastened by 0.5m/s (Fig. 10(c2)-(d2)). For storm Ciara, the MR increases current speeds as SLR increases within the MR site and along the main channel both downstream and upstream of the confluence of the Ribble and Douglas. Conversely, the MR decreases current speeds as SLR increases opposite to the MR site and beyond the main channel and upstream the confluence (Fig. 10(c2)-(b2)).

The impact of the MR on LWL is most noticeable in the vicinity of the MR site and upstream of it (Fig. 11). For storms Xaver and Ciara, the MR increases LWL with increasing SLR. We observe increases in LWL in the order of 0.3-0.4m for the smallest SLR (i.e. SLR = 0.24m) and of about 0.75m for SLR 1.02m on the saltmarsh platform, MR site and opposite to it (Fig.

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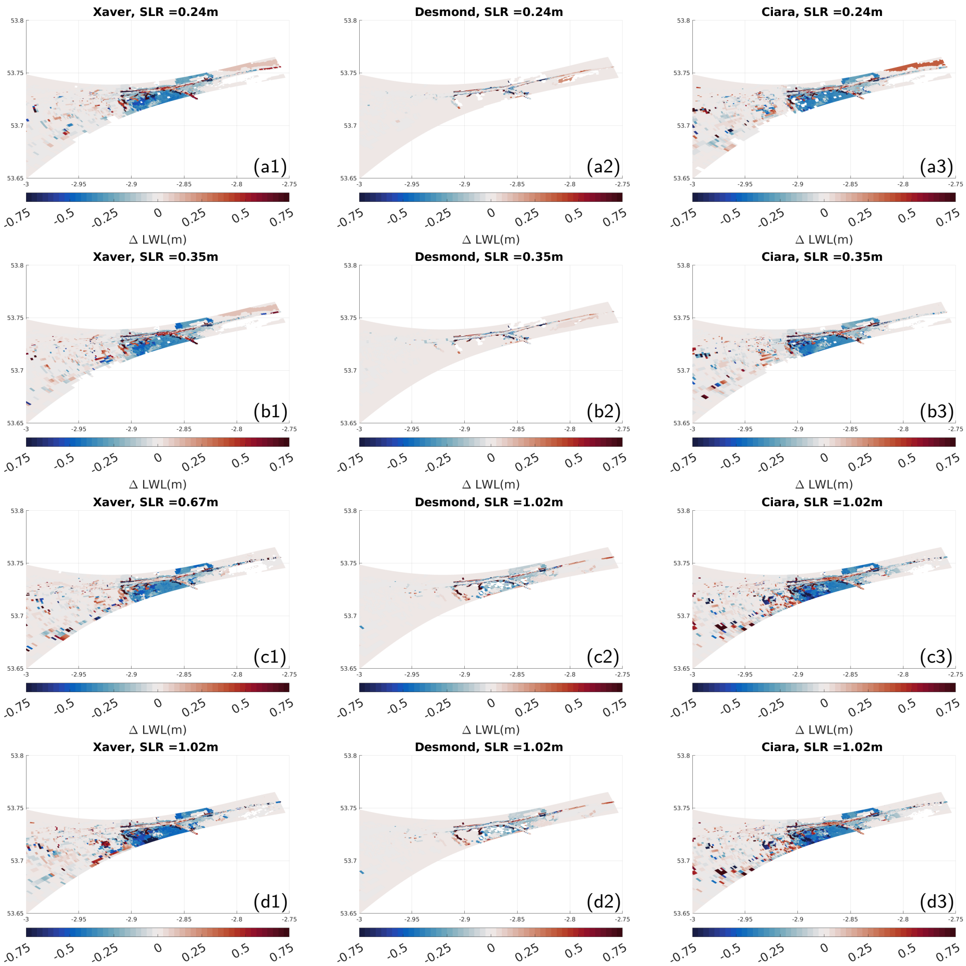

Figure 11. Changes in highest low total water level (LWL) due to the MR for the storms Xaver, Desmond, Ciara under the different sea level rise (SLR) considered. (a1)-(a3) Under SLR = 0.24m. (b1)-(b3) Under SLR = 0.35m. (c1)-(c3) Under SLR = 0.67m. (d1)-(d3) Under SLR = 1.02m. Red and blue indicate decrease and increase due to the MR.

11(a1)-(d1) and Fig. 11(a3)-(d3)) . Conversely, the decreases in LWL along the main channel are largest for the smallest SLR with decreases of about 0.5m for SLR = 0.24m and of about 0.15m for SLR = 1.02m for storms Xaver and Ciara respectively (Fig. 11 (a1)-(d1) and (a3)-(d3)). For storm Desmond under SLR = 0.24m and SLR =0.35 m, the impact of the MR on LWL is limited to the main Ribble and Douglas channels with increases about 0.3m that decrease further upstream to about 0.1m (Fig. 11(a2)-(b2)) . For storm Desmond under the two largest SLR scenarios evaluated, the impact of the MR on LWL extends beyond the main channels with increases of about 0.25m on the MR site and Ribble and Douglas channels (Fig. 11(c2)-(d2)).

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5 Discussion

The potential of vegetation to reduce water levels on open coasts is well acknowledged (e.g. Temmerman et al., 2023; Leonardi et al., 2018). However, the impact of MR within estuaries is less well understood, particularly for compound events and under future climate conditions. Synthetic analysis of the impact of MR generally focuses on maximum water level and coastal flooding hazard, hence focusing on extremes in ocean drivers (cf. Pontee, 2015; Kiesel et al., 2019; Townend and Pethick, 2002) without generally considering extreme river events or dynamically including SLR as we do here.

Through a set of consistent comparisons, we computed the impact of the MR in HOM on the estuary for critical values in terms of management (e.g. inundation area and time, TWL and LWL and their timings, current speed). We further isolated the impact of the MR on the tide dynamics, surge and river-induced water levels and their timing. We consider storms with strong narrative and legacy as highlighted by local actors. By analysing storms under SLR we are able to compare the level of adaptation that the MR imposes in the estuary vs. no intervention.

5.1 What are the impacts of the MR on present day dynamics in the estuary?

The success of MR as a NbS for coastal flooding reduction requires understanding its local impacts on the MR site and also the non-local impacts at the estuarine scale. MR in open coast or close to the mouth of estuaries can increase water levels because the intertidal area draws water during flood towards the MR and upstream of it (e.g. Townend and Pethick, 2002; Kiesel et al., 2019; Pontee, 2015). Saltmarshes and large MR in the inner reaches of estuaries may reduce water levels in the estuary because they can store a larger proportion of the local flood (e.g. Fairchild et al., 2021; Pontee, 2015; Smolders et al., 2015; Townend and Pethick, 2002). Conversely, small MR have been shown to have a limited effect in water levels (Bennett et al., 2020; Kiesel et al., 2019). Given the large size of HOM and its location in the upper reaches of the estuary, we would expect a reduction in water levels both at the local and estuarine scale. The MR in HOM is expected to provide flood protection to Hesketh Bank onshore the MR site due to increased roughness on the MR and, ultimately, by the upgraded landward dike against which TWL and surge pile up (see Fig. 3 and Fig. 6). While the cumulative drag effect of MR can reduce TWL further upstream (Smolders et al., 2015), water level attenuation in the Ribble is also driven by the extra storage space provided by the MR. This is shown by the increased inundation time and TWL over the MR site and downstream of it and the reduction of water levels due to each individual driver upstream of the MR site.

Previous studies had highlighted the link between storm surge attenuation, storm characteristics and landscape (Wamsley et al., 2010); here, we extend the analysis to compound events and the individual drivers (tide, surge and river-induced WL). Tidal channels and creeks, and vegetation blockages modify the flow momentum and redistribute water pathways driving desired impacts by reducing water levels upstream of the MR site but also unintended consequences at the estuary scale (e.g. while the MR reduces inundation time over the MR it increases it opposite to it and the MR increases river-induced water levels and LWL for all the storms, slows water at the confluence of the Ribble and Douglas were water tends to be blocked for longer periods when the MR is in place). During storms happening at spring tides (i.e. storm Xaver and Ciara), the MR reduces

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inundation time over the MR site by 15-80h and peak TWL upstream of the MR site by 0.1-0.2m, delays the arrival of peak TWL by several hours and intensifies currents along the new breaches and channels by 0.3-0.8m/s while slowing them at the confluence of both rivers by 0.6-0.8m/s. Conversely, during neap tides (i.e. Desmond) the MR enhances maximum TWL by up to 0.2m along the MR creeks and upstream of the confluence of the rivers, it also slows the propagation of TWL at the confluence of the rivers where the inundation time is increased by about 80h while over the MR it is reduced by the same order of magnitude. The MR amplifies LWL by 0.5-1.1m for all the scenarios considered. LWL are generally overlooked, however they have implications for navigation, drainage (critical following a flooding event) and water evacuation since they can cause blockages and backwater effects. The impact of LWL in the wider estuary was a blind spot for practitioners and researchers and highlighted by local farmers during the engagement in the project. The increased water levels and inundation duration can negatively impact the farmland and agricultural yield in the area. This effect can be exacerbated under SLR scenarios, when water elevation upstream of the MR site also rises and may further contribute to poor drainage. These negative effects beyond the MR site were brought to light repeatedly during the interactions with local actors.

When isolating water levels associated with each driver the MR generally reduces maximum water levels upstream of the MR site. The behaviour for each driver differs over the MR site and in some cases upstream of it. The MR reduces STR and MHHW due to the increase in tidal prism and intertidal area that causes a decrease in tidal amplitudes and high WL (Smolders et al., 2015; Townend and Pethick, 2002) and ultimately translates into water level attenuation. The MR increases the surge within the MR site because the restored vegetated habitat vegetation slows down tide and surge propagation thus increasing water depths (Wamsley et al., 2010; Kiesel et al., 2022, 2023). In the case of storm Xaver this increase extends offshore of the MR site as water is backed up by the MR site. The dikes surrounding the MR further limit the attenuation of surge in their vicinity since water piles up against them (Wamsley et al., 2010; Stark et al., 2016; Glass et al., 2018; Kiesel et al., 2019). The additional water storage provided by the MR as shown by the larger surges over the MR (see Fig. 6) reduces surges further upstream in the estuary (e.g. Pontee, 2015). The MR increases and delays river-induced water levels along the main channel, the southern flank of estuary and on the vicinity MR and the MR site itself (Fig. 7). This is likely due to the "backwater effect" caused by the combination of the MR and the natural saltmarsh that increase water levels in the offshore part of the estuary blocking and pushing back the river discharge. The reduction in STR and MHHW compensate the increases in surge and river-induced water levels due to the MR site resulting in overall reduced TWL upstream of the MR.

5.2 Future impacts of the MR in the estuary under SLR

In general the impact of the MR seems to be amplified under SLR. For storms during spring tides, the reductions in the inundation time are limited to the MR site and even shorten as SLR increases because the full domain becomes inundated. The MR is more effective in reducing inundation time as SLR increases for storms during neap tide. This is due to the SLR itself but also to the backwater effects of SLR and its propagation upstream causing water to overspill the main channels. SLR can increase the upstream propagation of water levels due to the reduction of pressure gradients (Hoitink and Jay, 2016); in the Ribble these increases are balanced by the increased tidal prism due to the MR that reduces TWL over the MR site and upstream of it. While for the lower SLR the westernmost part of HOMW in the vicinity of the drainage channel to the west of the MR shows increased TWL, as SLR increases the reductions in TWL extend over the full MR site and upstream of it. These increases in TWL for the lowest SLR may be due to the differences in bathymetry and to the water piling up against the embankment (e.g. Stark et al., 2016). Crucially, the beneficial impact of the MR in reducing upstream TWL increases with increasing TWL, while offshore TWL seem to decrease with increasing SLR. In terms of LWL, SLR leads to larger LWL in the estuary with increasing SLR reflecting the difficulty of waters to drain due to the backwater effect. Under SLR, the MR intensifies current speed along main channels and creeks which may have implications for sediment dynamics and the long-term evolution of the MR (cf. Section 5.4).

Under future SLR, the MR provides extra water storage space but, the ultimate protection during extreme events is given by the inner dike of the MR. Once the landward dike is overtopped, the current MR does not offer protection. This highlights the need for strategies that can be flexible and responsive to changing climate conditions and ensure future-proof adaptation. Given the location of HOM in a sparsely populated rural area it may be possible to define setback zones to allow for the accommodation of flood buffer areas and expansion of wetlands. However it requires careful consideration of the socio-economics especially given the public concerns regarding saltmarsh restoration and MR (Hudson et al., 2021; Apine and Stojanovic, 2026).

5.3 Community-informed research

The repeated interactions between scientists and local actors allowed us to frame the research questions together and define how to answer them. After the initial interactions, it became apparent the mismatch in the understanding of the estuary functioning of the different local actors. The initial aim of the study was to fill the gap literature on the impact of the MR at the estuarine scale under coastal events now and under future SLR. However after engagement with local actors, we better understood their needs and expectations and it became evident that compound events due to coastal and fluvial drivers and LWL were crucial in the estuary dynamics. As such, the storms that we analyse account for coincidence or close succession of coastal and fluvial drivers allowing us to explore the impact of the MR under compound events. Such compound events are not usually considered in MR studies that, contrary to this study generally, focus on sea drivers (e.g. Pontee, 2015; Kiesel et al., 2019; Townend and Pethick, 2002).

Our results show that the ability of MR to reduce water levels in estuaries may be misrepresented when compound events including river extremes are not considered since the MR worsens river-induced water levels across all the storms analysed. The impact of the MR in river-induced water levels can be of the same order or larger than those in surge or MHHW and STR (compare Fig. 7 and Fig. 6 and Fig. 5). This means that if we had not considered the river contribution and only analysed tide+surge events, we would have obtained a much more beneficial contribution of the MR in reducing water levels across the estuary. The different impact that the MR has on river-induced water levels for the three storms analysed reflects the importance of the non-linear interactions tide-river and river-surge. For example for storm Desmond, the impact of the MR is limited to the main river channels since the storm occurred during neap tides, while for Xaver and Ciara the impact of the MR extends beyond the river channels. The impact of the MR on river-induced water levels is important even when the river discharge presents

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moderate values as long as the storms generate a large surge or occur over spring tides tide as in the case of storm Xaver since non-linear interactions become important. Estuaries along the western coast of the UK, such as the Ribble, often experience concomitant high skew surges and high river discharge due to the fast catchment response time (Ward et al., 2018) and to the similar characteristics and track pathways of the storms that cause them (Hendry et al., 2019). Schemes for which river input has not necessarily been accounted for may protect from coastal flooding but impede river drainage and cause flooding landward of the scheme (e.g. Lymington on 25th December 1999, Hendry et al. (2019); Ruocco et al. (2011) or Lancaster during storm Desmond (Ferranti et al., 2017)). By not considering compound events including river events, the ability of MR to reduce waterlevels can be overestimated and communities can be left at risk. Since peak flows in the Ribble have increased since records began (NRFA, 2025b) and are expected to increase under climate change, they will potentially further contribute to increased river -induced water levels and LWL and flood risk in the estuary.

In the Ribble, the backwater effect is particularly noticeable when the MR is in place since it impedes the river water to freely drain and it raises LWL both now (see Fig. 4) and under future SLR (see Fig. 11). The little intervention and maintenance in MR sites once they are implemented (Dale and Arnall, 2024) may worsen the drainage problems highlighted in the Ribble by local actors and enhanced by new housing developments in the area. Poor drainage and lower flood storage capacity are well known characteristics of restored saltmarshes. Beyond impacting flood protection, poor drainage also impacts the biodiversity function of the ecosystem with already reduced plant diversity (Spencer et al., 2017) ultimately potentially defeating its primary purpose.

MR is often presented as a win-win solution for rural areas due to its potential to compensate habitat losses while providing protection by reducing water levels and providing other ecosystem services. However MR sites usually host highly valuable prime agricultural land (French, 2006) and local landowners perceive MR as an admission of failure in the face of rising seas, an increased flood risk and a lack of consideration of agricultural heritage and identity (Hudson et al., 2021). Incorporating local knowledge and ensuring repeated engagement with local actors has allowed in our study a shared understanding of the knowledge needs and ongoing issues affecting the estuary (e.g. river-induced water levels or LWL). This engagement between local actors and researchers is enriching for both parties; it allows consideration of the MR at the estuarine scale and within its social context and avoids blind spots and maladaptation (O'Leary et al., 2023). Further the networks created and the increased social capital can improve the adaptative capacity of the local community (Norström et al., 2020). The extra time required to establish MR and other NbS makes them appropriate for low-to-medium urgency scenarios (Morris et al., 2020) and can be used to establish similar local partnerships that allow more sustainable and equitable flood risk reduction strategies (Mortensen et al., 2024). Such partnerships have been shown to contribute to the longevity of solutions that require upkeep, maintenance and ongoing assessment (Mortensen et al., 2024) such as NbS.

5.4 Potential caveats and limitations

We explore the impact of the MR vs. doing nothing for present and future events using contemporary bathymetry and we do not include sediment dynamics or the unknown response of the system to SLR. We assume no storm damage (i.e. short-term erosion or wall breaching), this assumption holds for current scenarios; however, under future SLR, the high water load may damage the external wall increasing water levels in the main estuary (Pontee, 2015). Saltmarsh resilience to SLR depends on whether they can migrate further inland or whether they accrete at a similar pace to SLR (Schuerch et al., 2018; Crosby et al., 2016; Kirwan et al., 2016). In our simulations, the saltmarsh cannot migrate inland due to the landward embankment. In macrotidal environments, such as the Ribble, saltmarshes have been shown to be more resilient than those in micro or mesotidal environments (Kirwan et al., 2016; Masselink and Jones, 2024). In the Ribble, storms can potentially balance the impact of SLR over the saltmarsh (Pannozzo et al., 2021) and recent field studies (Muliawan et al., submitted for publication) indicate that the marsh in HOM is accreting fast enough to keep up with SLR.

We incorporate the impact of climate change exclusively through SLR. SLR has been shown to be the dominant contributor to future extreme water levels (Jevrejeva et al., 2023; Howard et al., 2019) and we do not consider changes on river discharge and storminess. The economic and social responses to rising seas are difficult to predict because the scale and nature of the problem are unseen and uncertainty is large. We omit considerations of other human disturbances (e.g. changes to landscape in habitats or land use) that play a major role in coastal morphology and the long term persistence of saltmarshes (Temmerman et al., 2023). It is unclear whether these ecosystems will manage to adapt to changes in the environmental conditions (e.g. depth of saltmarsh, temperature or salinity) or reach a tipping point, collapse and change to an alternate ecosystem (Bouma et al., 2014; Temmerman et al., 2023).

6 Relevance and Conclusions

Part of the strength of this research is its place-based nature, and that is also part of its limitation. The choice of coastal protection is place specific (Villasante et al., 2023) and the effectiveness of NbS is highly influenced by the local context (Bouma et al., 2014). While most of the MR are limited in size, HOM exemplifies the impact a MR of considerable size can have at estuarine scale. Our work highlights the importance of including local actors from the early stages of the project. In the Ribble, local actors pointed to the relevance of compound events and impacts beyond the intervention site. During this study the repeated interactions between local actors and researchers, allowed researchers and local actors to define together the knowledge needs and the key research questions and ensured that blind spots were avoided. Site-specific studies like this one help fill the existing gap in the performance of MR to reduce water levels driven by compound events both now and in the future. The impact of the MR is localised on the vicinity of the MR site and upstream of it. The MR reduces the inundation time while consistently increasing it opposite to the MR site. The MR delays and reduces TWL by 0.1m-0.2m over and upstream of the MR site during spring tides but increases TWL by the same range downstream of the MR and for storms during neap tides potentially impacting drainage and infrastructure. The MR increases LWL by 0.7-0.8m for all the storms considered potentially worsening backwater effects and impacting drainage and sediment dynamics and delays the arrival of maximum TWL for all the storms considered. These impacts are amplified under SLR with reductions in TWL of up to 0.2-0.3m under future SLR. We found that the MR continues to reduce upstream TWL as SLR increases pointing to the potential of MR to enhance coastal resilience in the future. In terms of LWL, SLR leads to larger LWL in the estuary with increasing SLR reflecting the difficulty of waters to drain due to the backwater effect. While the MR has the potential to reduce surges it consistently increases river-induced water levels, underscoring the importance of considering compound events when analysing the impact of a MR at estuarine scale since omitting river events may lead to the overestimation on the level of coastal protection that the MR can provide. Our study evidences the complexity and challenges of implementing MR and the pertinence of incorporating local knowledge in order to achieve effective mitigation and adaptation at estuarine scale through strategies that work both short and long term. The causes and consequences of (extreme) events involve complex natural processes but also societal factors. Combined with socio-economic studies, works like this one can be used to guide policy and management decisions.

Data availability. Data will be uploaded to a public repository once review process is completed

Appendix A: Additional Materials

500 This section includes figures with the absolute values for the runs without intervention (no MR) and with intervention (MR) as well as the difference between both runs as "no MR - MR" for each variable.

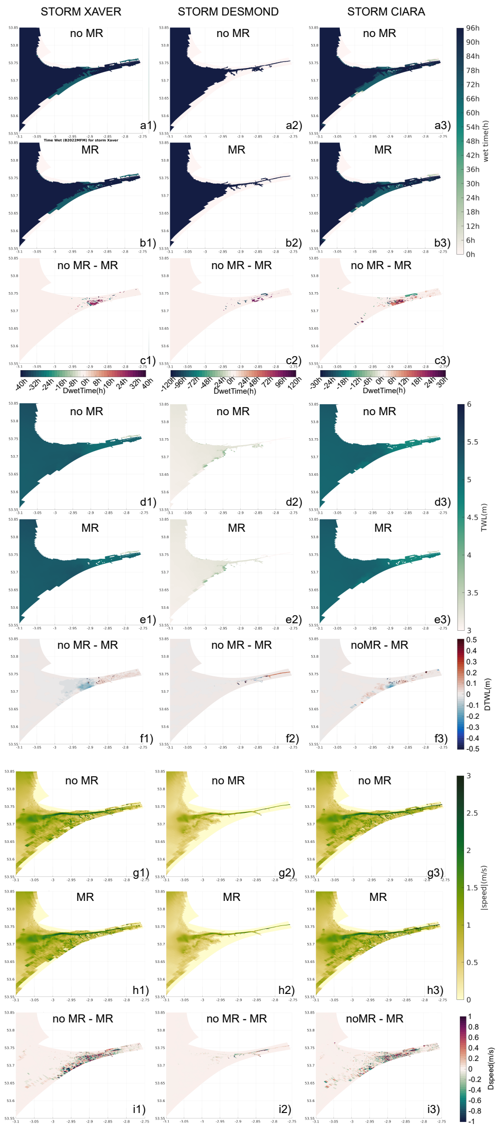

Figure A1. Impact of MR in TWL for the storms Xaver, Desmond, Ciara. a1), a2), a3) inundation time prior to MR. b1), b2), b3) inundation time after MR. c1) c2) c3) Change in inundation time once the MR is in place. Red and blue indicate respectively decrease and increase due to the MR. d1), d2), d3) maximum TWL prior to MR. e1), e2), e3) maximum TWL after MR. f1) f2) f3) Change in maximum TWL once the MR is in place. Red and blue indicate respectively decrease and increase due to the MR. g1), g2), g3) maximum current speed prior to MR. h1), h2), h3) maximum current speed after MR. i1) i2) i3) Change in maximum current speed once the MR is in place. Red and blue indicate respectively decrease and increase due to the MR.

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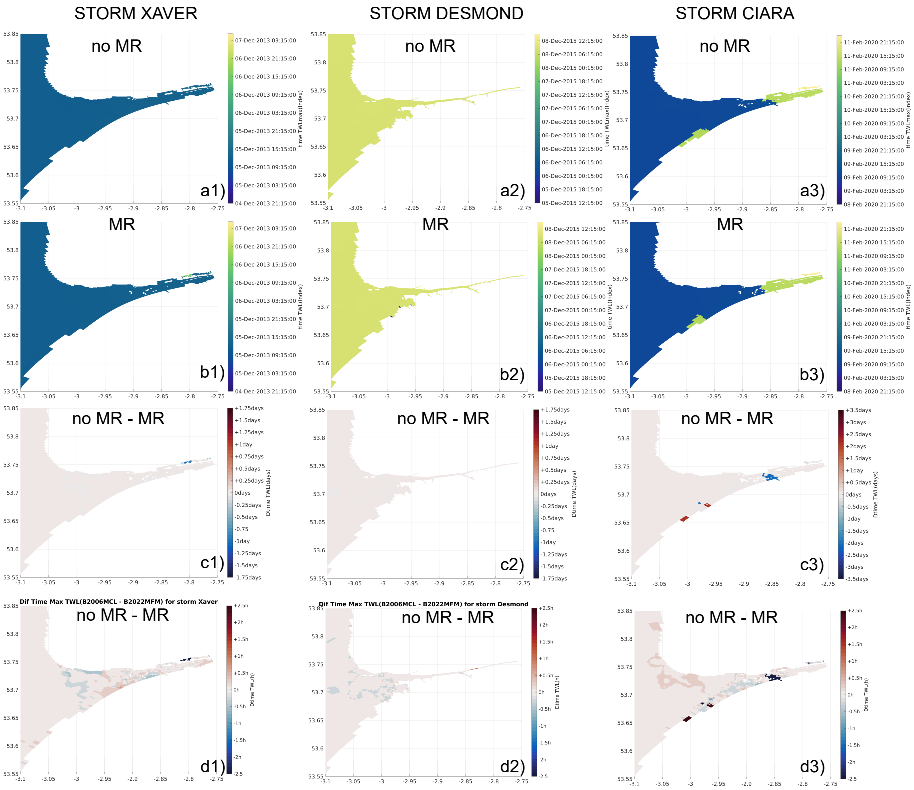

Figure A2. Impact of MR on the time of maximum TWL for the Xaver, Desmond, Ciara. a1), a2), a3) time for max TWL prior to MR. b1), b2), b3) time for max TWL after MR. c1) c2) c3) Change time (in days) for max TWL once the MR is in place. Red and blue indicate respectively advance and delay in the time for max TWL due to the MR. d1), d2), d3) Change time (in hours) for max TWL once the MR is in place. Red and blue indicate advance and delay respectively in the time for max TWL due to the MR.

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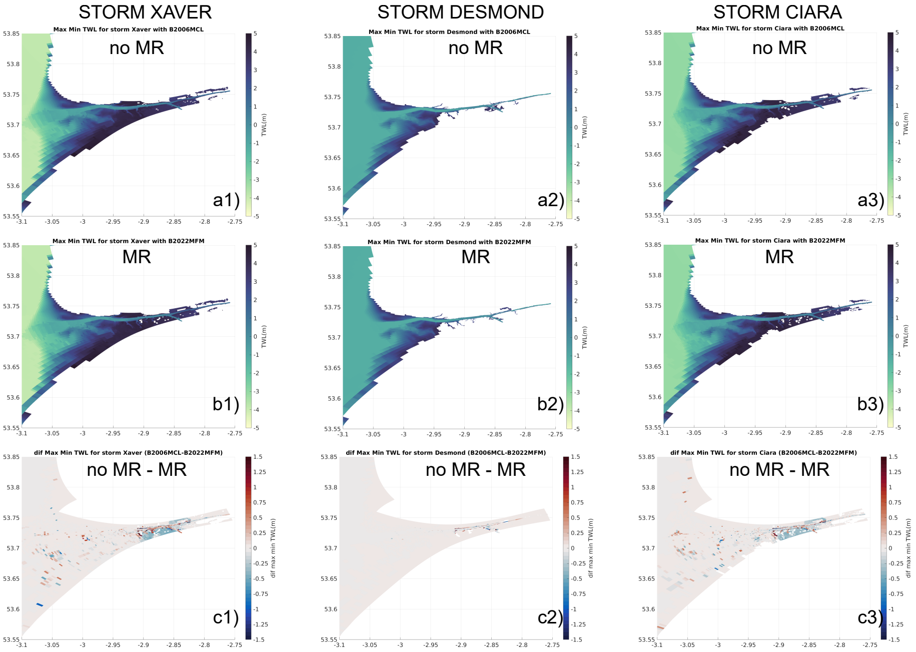

Figure A3. Impact of MR on the maximum low TWL for the storms Xaver, Desmond, Ciara. a1), a2), a3) max low TWL prior to MR. b1), b2), b3) max low TWL after MR. c1) c2) c3) Change in max low TWL once the MR is in place. Red and blue indicate respectively decrease and increase in maximum low TWL

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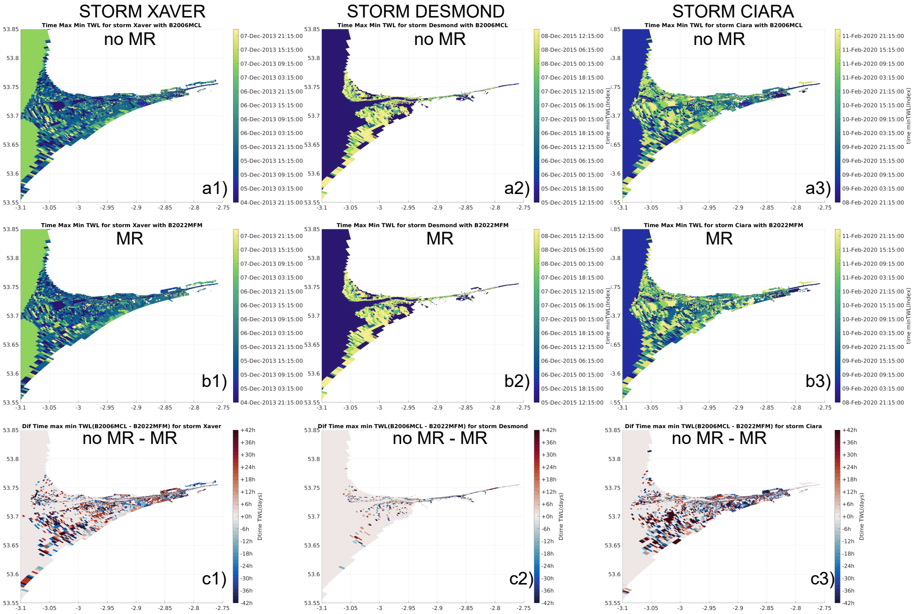

Figure A4. Impact of MR on the time of highest lowTWL for storms Xaver, Desmond, Ciara. a1), a2), a3) time for max low TWL prior to MR. b1), b2), b3) time for max TWL after MR. c1) c2) c3) Change time (in hours) for max low TWL once the MR is in place. Red and blue indicate respectively advance and delay in the time for max TWL due to the MR.

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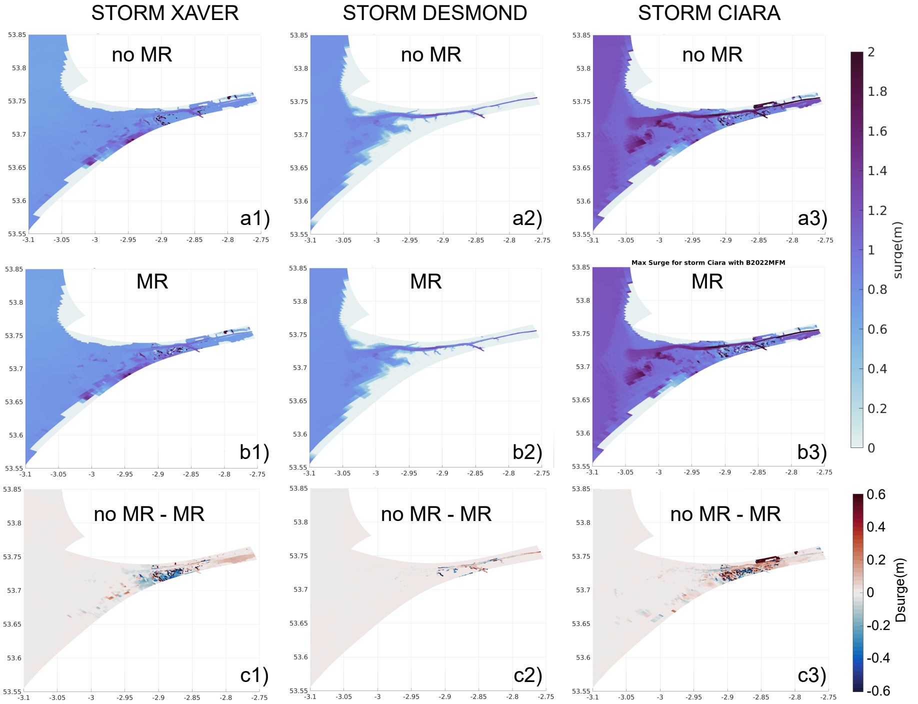

Figure A5. Impact of MR on the surge for storms Xaver, Desmond, Ciara. a1), a2), a3) max surge prior to MR. b1), b2), b3) max surge after MR. c1) c2) c3) Change in max surge once the MR is in place. Red and blue indicate respectively decrease and increase in the surge due to the MR.

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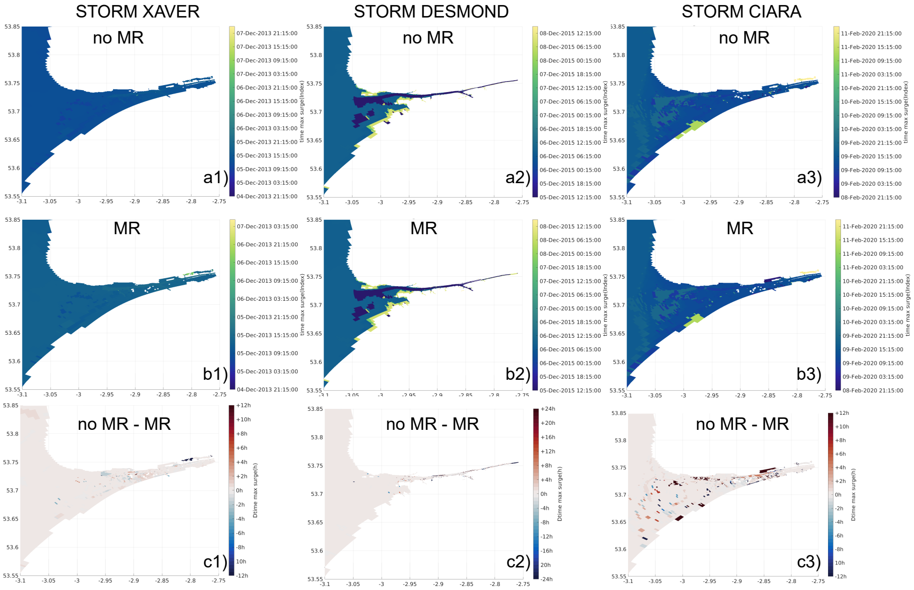

Figure A6. Impact of MR on the time of maximum surge for storms Xaver, Desmond, Ciara. a1), a2), a3) time for max surge prior to MR. b1), b2), b3) time for max TWL after MR. c1) c2) c3) Change time (in hours) for max surge once the MR is in place. Red and blue indicate respectively advance and delay in the time for max surge due to the MR.

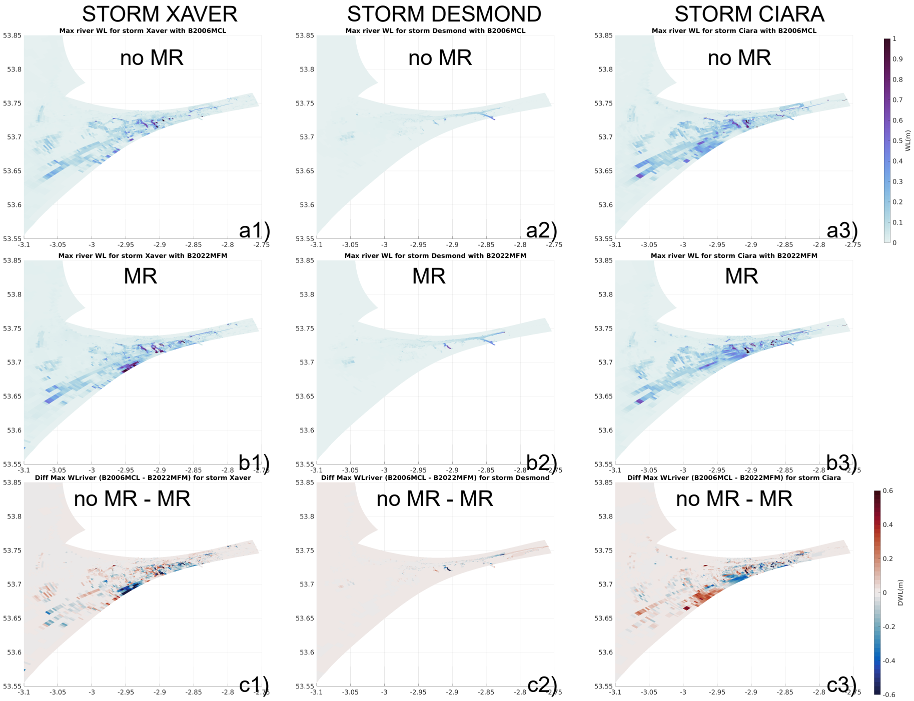

Figure A7. Impact of MR on the water levels due to river discharge for storms Xaver, Desmond, Ciara. a1), a2), a3) max river induced water level prior to MR. b1), b2), b3) max river induced water level after MR. c1) c2) c3) Change in surge once the MR is in place. Red and blue indicate respectively decrease and increase in the river-induced water level due to the MR.

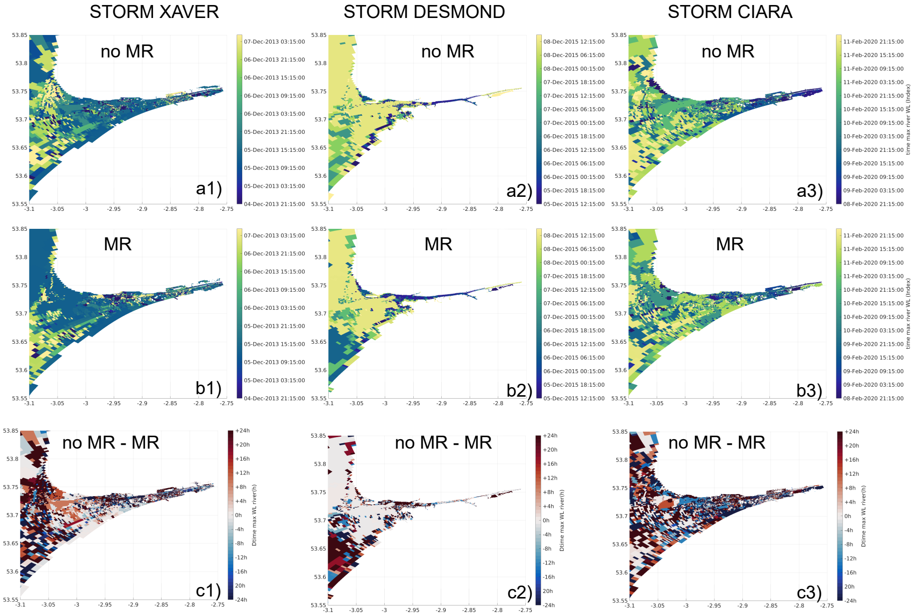

Figure A8. Impact of MR on the time of maximum river induced WL for storms Xaver, Desmond, Ciara. a1), a2), a3) time for max river induced water level prior to MR. b1), b2), b3) time for max river induced water level after MR. c1) c2) c3) Change time (in hours) for max river-induced water level once the MR is in place. Red and blue indicate respectively advance and delay in the time for max surge due to the MR.

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Competing interests. The authors declare no competing interests

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