Evaluating the viability of coastal wet grassland to a changing management regime through flood hazard modelling

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Highlights

- **Preventing breaching is key for sustainability of embanked coastal habitats**
- **Reprofiling and lowering of embankments may 'buy' extra years of flood defence**
- **> 10 days inundation potentially a key threshold for wet grassland community change**

Abstract

The high-risk nature of low-lying coastal areas means that many are characterised by protective dikes, sea walls, and earthen embankments. Across Europe, such structures are employed to limit landward sea flooding and have been used historically to reclaim wetlands, many of which have since gained international protected habitat status. Sea level rise and storms threaten the future viability of fixed flood defences which will be overtopped with increasing frequency and, in extreme cases, breached. This raises questions surrounding defence maintenance and the fate of the reclaimed wetlands they encircle and support. One approach is to design defences with the expectation that they will be overtopped during extreme events, but that catastrophic failure as a result of breaching will be prevented. Such an approach was recently implemented at Blakeney Freshes, North Norfolk Coast, UK, an embanked area of reedbeds and coastal wet grassland. Lowering and widening of the Freshes embankment was undertaken following extensive breaching during the 5 December 2013 storm surge. In this paper we develop and apply a numerical model chain, comprising storm surge water levels, waves, and overtopping, to explore inundation extent, depth, and duration resulting from storm surge induced flooding under several sea level rise scenarios. Modelling results revealed that 99.5 % of the flood volume of the 2013 event resulted from embankment breaching. Simulating the same storm event after embankment reprofiling shows that flooding of the Freshes is reduced by 97 %, largely because the lower, wider embankments preclude breaching. However, under future sea level rise scenarios, storm surge induced overtopping results in increased inundation depths and drainage times, raising questions regarding the resilience of vegetation communities within the Freshes. By 2100 under the lowest SLR scenario, and by 2050 under the mid SLR scenario, over half of the Freshes will be inundated for >10 days, a potentially critical threshold for current wet grassland survival. Our findings suggest that while effective defence redesign may increase the viability of reclaimed wetland habitats in the short term, as sea levels rise, lengthened inundation durations may render these habitats increasingly vulnerable to ecosystem change under extreme events.

Keywords

Overtopping, breaching, reclaimed wetland, storm surge, embankment, coastal protection

Introduction

Coastal flood risks are the product of hazard and vulnerability, and are expected to increase over the coming decades. Climate change drives hazards of accelerating rates of sea level rise and potential increasing storminess (Nerem et al., 2018; Hartmann et al., 2013), which accompanies increased vulnerability/exposure of the world's low-lying coastal zones arising from greater human occupancy (Hinkel et al., 2014).

The traditional response to the risk of coastal flooding, over many centuries, has been to build defences such as dikes, sea walls and earthen embankments. However, such fixed defences bring with them continued and costly maintenance regimes, exacerbated by the need to repeatedly heighten and widen such structures in response to changes in mean water level resulting from sea level rise. Thus, for example, it has been calculated that the mean increase in coastal flood defence height required in Europe to keep current risk constant will be 0.5 m by 2050 and 1 m by 2100 (Vousdoukas et al., 2018). Whilst in some locations the protection of people and assets means that hard defences are the only option, in other locations rising costs, and the dis-benefits resulting from changing flood and erosion regimes from interference with natural coastal dynamics, has forced more attention to be directed towards non-structural responses to coastal change (e.g. Temmerman et al., 2013).

Socio-political landscapes have also been re-configured over the last fifty years around a much greater concern for the maintenance of coastal biodiversity and coastal ecosystem services (MEA, 2005). European legislation, in the form of the EU Habitats Directive, Birds Directive and Water Framework Directive, has designated large areas of reclaimed, often grazed, wet grasslands as Special Areas of Conservation. Designation has been on the basis of their unique assemblages of plants, invertebrates and birds, in part related to a hydrological regime that allows drainage of freshwater through sea walls via networks of drainage ditches, culverts and tidal sluices. Such designations, however, effectively block the restoration of full tidal exchange (Pethick, 2002). Nevertheless, even if embankments between seaward salt marshes and landward wet grasslands cannot be dismantled, a coastal defence function can be provided by allowing the overtopping of defences by storm waves and tidal surges during extreme events and hence the temporary storage of floodwaters over wet grassland surfaces. Thus, for example, in the UK east coast storm surge of 5 December 2013, Spencer et al. (2015) and Skinner et al. (2015) document the flooding of 1,000 ha of coastal habitats and agricultural land on the Norfolk and Suffolk coasts and 7,000 ha of urban, industrial and agricultural areas in the Humber estuary respectively. It is clear, therefore, that significant volumes of floodwater may be stored in this way under extreme conditions making a real difference to event-related coastal safety.

Designing for such storage is challenging and location-specific; many questions arise. In the case of earthen embankments, how can defences be designed to allow for overtopping but not risk defence breaching (where repair costs are considerable and access routes along defences can be legally significant)? What is the most appropriate trade-off (i.e. bank height) between allowance of more frequent inundation of freshwater wetlands and the long-term maintenance of grazing wet grassland biodiversity and ecosystem services? How might the nature of this trade-off change with rising sea levels and increased storminess? Rather than waiting for such a changed flooding regime to occur, and reacting to it, environmental modelling offers the possibility of scenario testing for future conditions not yet realised by the ecosystem.

In this paper we address these issues and approaches through a modelling study of the Blakeney Freshes, a site of nationally and internationally recognised wet grassland on the barrier coastline of North Norfolk, UK east coast. Specifically, in this paper we:

1) Build and calibrate a model train framework to evaluate the impact of a major storm surge (5 December 2013) on an embanked wet grassland and reedbed area, comparing model outputs with known patterns of seawater flooding and drainage;
2) Evaluate the management response to this storm surge flooding event – the repair and re-profiling of earthen embankment defences – and compare the impacts from breaching of a traditional high and narrow defence line to that of overtopping of a reconfigured defence of lower crest height and broader cross-sectional profile;

3) Model future flood depths, extents and durations from a combination of 5 future sea level rise scenarios, variously to 2050 and 2100, in combination with a 2013-type storm, under this reconfigured defence; and
4) Explore how shifts in flooding regime, as a result of sea level rise and management changes, may impact coastal wet grassland vegetation communities.

Location

The 45 km long North Norfolk coast is a barrier island coastline, lying between the chalk headland at Hunstanton and 20 m high cliffs in glacial deposits at Weybourne (Figure 1a, b). The 2 km wide low-lying coast is characterised by extensive subtidal and intertidal mudflats and sandflats; gravel and sand barriers separated by tidal channels and ebb tide deltas; and back-barrier channels (or 'creeks') and saltmarshes (Andrews et al., 2000). Landward margins are characterised by sand dunes (some with plantation forest), brackish reedbeds and, particularly, > 800 ha of wet grassland in areas of reclaimed saltmarsh (Figure 1). Towards the eastern end of this frontage, the Weybourne to Cley gravel ridge, which terminates in Blakeney Point, is a large gravel and sand system that extends westwards from Sheringham for over 17 km.

Blakeney Freshes, a 160 ha area of embanked wet grassland and reedbeds, is located behind this gravel barrier at the transition between the back-barrier wetlands of the Cley and Salthouse Marshes, the deeper water of Blakeney Harbour and the tidal wetlands of the Morston Marshes; on its southern landward margin, the topography rises rapidly to 35 m above sea level less than 1 km inland (Figure 1c). The Freshes were originally tidal saltmarshes on the western margin of the paleo-estuary of the River Glaven. In the early 13th century the estuary was ca. 750 m wide and yet to be closed by the westward extension of the Blakeney Point. It is possible that the marshes developed under the protection of the spit; by the late 15th century the spit terminus was opposite the modern village of Blakeney (Pethick, 1980). The Salthouse Marshes were embanked in the period 1637 – 1649 and the Cley Marshes and the Blakeney Freshes in 1650 or shortly thereafter (Cozens-Hardy, 1927; Hooton, 1996). Faden's 1797 map of Norfolk, surveyed in 1790-1794, clearly shows the embankment along the northern margin of the Freshes and identifies the Blakeney Marsh (the western section of the Freshes) and Wiveton Marsh (to the east) as 'drained' (Hooton, 1996). Since that time, the embankment has been periodically damaged, repaired and re-built; prior to December 2013, the 3.5 km-long bank had an elevation ranging in height from ca. 5.0 to 5.6 m ODN (Ordnance Datum Newlyn where 0.0 m ODN approximates to mean sea level).

Inside the encircling embankment, the topography of the Freshes ranges from 1.1 to 5.3 m ODN with the vegetated surfaces having an average elevation of 1.96 m ODN. The undulating surface topography is dissected by both sinuous channels, remnants of former saltmarsh creek systems, and a network of linear drainage ditches; residual water surfaces are typically at 1.70 m ODN. The main drainage system runs east to west across the site, linking freshwater input from the River Glaven in the east to two tidal sluices on the western margin; these sluices allow gravity drainage at times of low water into the maintained channel between Blakeney Quay and the outer Blakeney Harbour. The Blakeney Freshes is an example of a lowland wet grassland landscape, transitional between terrestrial and aquatic systems, with an abundance of grasses, reeds and sedges and characterised by periodic flooding with fresh or brackish water and a seasonally high water table. Crucially, wet grasslands are maintained by disturbance which prevents the establishment of trees or shrubs. Disturbance may come from flooding pulses and/or from a land management system that directly supports domestic herbivores, either through grazing (pastures) or hay fodder (meadows (Joyce et al., 2016)).

The majority of the Freshes is coastal wet grassland, dominated by Meadow Barley Grass (*Hordeum secalinum*), with perennial ryegrass (*Lolium perenne*), Yorkshire Fog (*Holcus lanatus*) and other perennial grasses. On the western margin of the site, and along the main drainage channel, is an area of Common Reed (*Phragmites australis*) and False Oat-Grass (*Arrhenatherum elatius*). The north and west of the site experiences saline intrusion, leading to the development of mosaics of maritime grassland and upper saltmarsh vegetation communities. Elsewhere low-lying ponds and artificial scrapes are fringed by reeds and sedges; low areas on the southern margins of the site are characterised by Tufted Hair Grass (*Deschampsia cespitosa*). The drainage ditches are dominated by *Phragmites australis*, with Bulrush (*Typha latifolia*), sedges and typical freshwater aquatic plants. The area is managed under a UK Government DEFRA Countryside Stewardship (CS) agreement with The National Trust for which the specific objectives are 'to produce ideal conditions for breeding and over-wintering wildfowl and waders, by means of controlled grazing and manipulation of water levels, and to maintain and enhance the traditional coastal grazing marsh landscape'. The grassland communities are grazed by cattle on rotation over the summer months and the reedbeds are periodically harvested. Wildfowling is a consented activity and several artificial flight ponds have been created within the Freshes. On their seaward margins, the earthen embankments support floristically diverse upper, middle and pioneer saltmarsh communities (2.04 to 3.40 m ODN), down to gravel beaches or unvegetated mudflats.

Process environment

Tidal levels and Extreme Water Levels

The North Norfolk coast has a macro-tidal regime, with a mean spring tidal range of 6.5 m in the west at Hunstanton, reducing eastwards to 4.4 m at Cromer. Mean High Water Springs at Blakeney is reported as 2.60 m ODN. The comparable figure for the Cromer Tide Gauge, 25 km to the east (Figure 1b), is 2.15 m ODN with a Highest Astronomical Tide of 2.79 m ODN. Highest Astronomical Tide (HAT) at Blakeney is not known but is probably ca. 3.3 m

ODN (EACG, 2010). In a UK-wide assessment of coastal flood boundary conditions (EA, 2018), the 1 in 1 year extreme water level at the entrance to the Blakeney Harbour Channel was calculated at 3.72 m ODN, with the 1 in 10 year and 1 in 100 year levels as 4.13 and 4.63 m ODN respectively, the latter ca. 40 to 90 cm below the minimum height of the original Freshes embankment.

Waves

For the period 2006 – 2017, annual mean significant wave heights (Hs) of 0.80 – 1.00 m were recorded at Blakeney Overfalls (10 km offshore, 18 m water depth; Figure 1b); a maximum wave height of 5.56 m was recorded in December 2009. Between 2006 and 2009, four inshore stations (5 - 7 m water depth) along the North Norfolk coast recorded annual mean significant wave heights (Hs) of 0.49 – 0.73 m, with maximum significant wave heights (Hs_{max}) of between 2.7 – 4.1 m (Spencer et al., 2015). The predominant wave direction is from N to NNE. The record is dominated by locally generated wind waves (3 - 7 s peak period) with occasional swell waves from the NW during stormier periods caused by the passage of low pressure systems to the north.

Extreme events: southern North Sea storm surges

The partially enclosed, relatively shallow southern North Sea is susceptible to occasional storm surges which, particularly when they coincide with high spring tides, can elevate peak water levels considerably above the predicted extreme levels (Haigh et al., 2016). Surges are potentially highly damaging when accompanied by large onshore waves at, or close to, maximum water levels (Brooks et al., 2017). Twenty-six storm and surge events have impacted the North Norfolk coast between Wells-next-the-Sea and Salthouse since 1665 (Brooks et al., 2016; Garnier et al., 2018; and recent unpublished field surveys). In modern times, the most catastrophic events were the storm surges of 31 January – 1 February 1953 (described as the worst natural disaster to impact NW Europe in the post-WWII period with 65 fatalities on The Wash and North Norfolk coasts including 3 deaths at Cley; Baxter, 2005), 11 January 1978 (Steers et al., 1979) and 5 December 2013 (Spencer et al., 2015). A 1953 flood level of 6.07 m ODN is recorded at Blakeney Quay but it seems likely that this level represents the combination of surge and maximum wave action; indeed Grove (1953) reported maximum flood levels in Blakeney of 4.27 - 4.88 m ODN. As Steers notes 'the most obvious effect of the storm was the flooding of all the reclaimed marshes' (Steers, 1953, 287); this included the flooding of the Blakeney Freshes. In January 1978, Steers et al. (1979) surveyed a surge level of 4.90 m ODN at Blakeney Quay. At Salthouse the gravel ridge was overtopped and lowered by 1m with the overwash volumes sufficient to flood the freshwater wetlands and the coast road.

Storm surge of 5 December 2013

In the Humber estuary, The Wash and on the North Norfolk coast, the storm surge of 5 December 2013 produced higher maximum water levels than those associated with the 1953 event. Maximum water levels for locations between Wells Quay and Salthouse were between 5.02 and 5.61 m ODN. Two major breaches took place in the Weybourne-Cley gravel ridge, accompanied by the development of extensive washover fans, the infilling of near-barrier saline lagoons and the inundation of 91 ha (one third of the total area of backbarrier wetland) of the Cley to Salthouse Marshes. As in 1953, and to a lesser extent in 1978, there was flooding of other reclaimed marshes along the coast, giving a total inundated area of 479 ha (Spencer et al., 2015).

Spencer et al. (2015) document the passage of the surge southwards along the UK east coast over the afternoon and evening of 5 December 2013; water levels peaked at 17:15 (level of 4.32 m ODN), 19:00 (5.21 m ODN), and 22:45 (3.22 m ODN) UTC at Whitby, Immingham and Lowestoft respectively (Figure 1a). The Wells Harbour Quay was flooded between 17:30 and 22:00 UTC with the maximum water level experienced at 19:15 – 19:30 UTC. The highest waves recorded during the passage of the surge, with a significant wave height (Hs) of 3.8 m, occurred at Blakeney Overfalls at 16:30 and 17:30 UTC. Wave direction during the passage of the surge showed a gradual change from North-Westerly to Northerly at Blakeney Overfalls for the period 12:00 to 23:00 UTC. The interaction of this wave field with the bathymetry of the Blakeney Harbour channel meant that considerable wave action was focussed into the western and north western margin of the Blakeney Freshes embankment.

The earthen bank enclosing the Freshes was breached in 13 places, over a total distance of 550 m. The breaches were in three spatial clusters but most notably on the western margin (Figures 2a-2c and 6). From observations of the impact of this event elsewhere on the North Norfolk coast (Spencer et al., 2015), and following Steers (1953), it is likely that surge-related overtopping led to bank erosion and mass movements on the inner embankment face, with failure migrating progressively seawards towards the outer slope (Figures 2a, 2c). However, the presence of extensive alluvial fans within the Freshes at points of bank failure at the site's NW corner (Figure 2b) suggests that some collapse was of a more catastrophic implosion; the presence of such debris fields after the 1953 surge was attributed to a mechanism of ‘uplift failure’ of embankments with high porewater pressures developing in silty sands near the base of the structure (Marsland, 1988). Elevations of surge driftlines to the east of Blakeney village, behind the western margin to the Freshes, recorded maximum water level elevations of 4.91 – 4.95 m ODN, suggesting saltwater inundation to a depth of ca. 3 m over vegetated surfaces.

In order to aid removal of floodwater, the UK Environment Agency restored the southern culvert to gravity drainage on 30 January 2014. Between July and December 2014, the Agency repaired the failed sections of The Freshes embankment, in places re-profiling with a cross-shore profile characterised by a lower elevation (a design height of 4.25 m ODN compared to the pre-surge heights in the range 5.0 to 5.6 m ODN) and wider crest and shallower slopes than the pre-surge configuration (Figure 2d). It has been argued by the Agency that this geometry will be more resilient to damage and failure than the previous structure during future surge events.

Methods

Modelling 2013 storm surge flooding of the Blakeney Freshes

The approach to modelling the 2013 flood extents involved a nested, four-stage approach (Figure 3a) which models the transformation of waves and tides from offshore to nearshore, calculates wave overtopping and flow discharge into a flood inundation model at Blakeney Freshes (methodology adapted from Jäger et al. 2018).

Bathymetry and topography

Bathymetric and topographic data were obtained from the UKHO (UK Hydrographic Office) MEDIN bathymetry dataset, UK Environment Agency (EA) and EDINA Digimap Ordnance Survey Service (www.digimap.edina.ac.uk). Bathymetric data had a resolution of 1 to 200 m, and topographic data ranged in resolution from 1 to 5 m. At Blakeney Freshes, 1 m resolution DTM LiDAR data was obtained from before (January/ February 2014) and after the embankment reprofiling (November 2015). Along this coastline the datum shift between the bathymetry Chart Datum (CD) and the topography Ordnance Datum Newlyn (ODN) differs across the area, from ca. 1.8m at the eastern end to ca. 3.5 m to the western end. In order to join the bathymetric and topographic datasets, the UK Hydrographic Office (UKHO) Vertical Offshore Reference Frame (VORF) surface (Lessnoff, 2008) was used.

TELEMAC 2D hydrodynamic model

A 2D TELEMAC hydrodynamic model (Hervouet, 2000; Figure 3b) was used to calculate tidal water levels over a model domain spanning ca. 50 km offshore to the 10 m ODN land contour (model grid of 12,779 elements). Grid resolution ranged from ca. 12km offshore gradually increasing to ca. 15 m in the Blakeney Harbour Channel. The TELEMAC model was forced with hindcast modelled water level and velocity timeseries (hourly) at 12 boundary locations from the CS3X tidal surge model (National Oceanography Centre, UK). Wind conditions from the Met Office Numerical Prediction model (10m wind field) were interpolated from a 12 x 12 km grid onto the TELEMAC grid. A fixed bottom friction was applied using the Nikuaradse law with a friction coefficient of 0.0125. Turbulence was modelled using the Smagorinsky model (Hervouet, 2000).

2D nested spectral wave models (SWAN)

A series of nested SWAN models (Booij et al., 1996, Figure 3b), of grid resolution 5 km, 500 m and 15 m, was used to accelerate computational time and improve accuracy in the complex topography nearshore. Wave energy dissipation due to the presence of saltmarsh vegetation was included in the small scale SWAN model using the method of Suzuki et al. (2012). Representative vegetation characteristics were derived from published data for UK East coast and North West European Saltmarshes, with vegetation height, H_v = 0.11 m (Möller et al., 1999), vegetation diameter, D_v = 0.00125 m (Möller et al., 2014), and plant density, N_v = 1,061 individuals m^{-2} (Möller, 2006).

The largest SWAN model was driven by 2D spectra and wind conditions from the UK MetOffice (UKMO) Wavewatch III (WWIII) North Atlantic European model (Bunney and Saulter, 2015) with a resolution of approximately 12 km. The water level and flow velocities were obtained from the TELEMAC model and interpolated onto the grids.

Overtopping model

Water levels and wave conditions at the margin of the earthen embankment surrounding Blakeney Freshes were used as input to overtopping calculations at 72 locations (ca. 50 m spacing) along the embankment (Figure 3c). Wave overtopping was calculated using the empirical formulas for wave overtopping as set out by the EurOtop manual (Van der Meer et al., 2016).

Blakeney Freshes inundation and drainage model

The resulting overtopping discharge timeseries (20 min resolution) was then used to drive a flood inundation model for the Freshes (Figure 3c). The inundation model was created using TELEMAC 2D, consisting of the area within the earthen embankment surrounding Blakeney Freshes (203 ha) and the Blakeney Harbour Channel. The model used an unstructured grid with a resolution of ca. 2.5 m, and a Manning roughness coefficient of 0.02, based on land cover data.

Drainage of the Freshes was incorporated via two tidal culverts (with non-return gravity gates on their seaward exits) and infiltration. One-way flow through the culverts was calculated using the methodology of Smolders et al. (2016) as a function of the difference in water levels between the inlet and predicted tidal water levels at the outlet. Flow was thus only possible at times of low water levels at seaward culvert exits (2 culverts width 0.75 & 0.9 m and length 20.51 & 20.70 m, respectively. Entrance head loss coefficient = 0.5, exit head loss coefficient = 1, loss coefficient due to flap = 1, Manning Strickler roughness coefficient = 0.015). Infiltration rates within Blakeney Freshes were measured in the field using a ring infiltrometer, generating infiltration rates of 8.97 and 20.66 mm/day for wet grassland and reedbed respectively. The mean infiltration rate for the Freshes was calculated as the product of the total area of both wet grassland and reedbed (93.03% and 6.97%, respectively (Natural England Priority Habitat Inventory)), and their infiltration rate. The site-mean infiltration rate was found to be 9.79 mm/day.

Model Calibration

Calibration of the regional scale TELEMAC and the SWAN models was undertaken for the period 30/10/2007 00:00 to 09/11/2007 15:00 UTC. This calibration period was chosen as there were a large number of tide gauge and water depth measuring wave buoys in operation in the study area during this period. It also included the southern North Sea surge event of 8 November 2007, which enabled calibration under extreme water levels. The TELEMAC modelled water levels were compared with the Cromer tide gauge and water depth measurements from the Cley Acoustic Wave and Current (AWAC) nearshore (7 m water depth) buoy (Figure 1). Figure 4 presents the water level time-series comparing modelled and measured data for these locations; RMSE error terms were 0.34 m and 0.15 m respectively. The wave conditions calculated by the nested SWAN models were compared with the observational record at Blakeney Overfalls waverider buoy (10 km offshore, 18 m water depth) and the Cley AWAC buoy (Figure 5). Significant wave heights were replicated well by the model, with RMSE error terms of 0.39 m and 0.43 m for the Blakeney and Cley locations respectively.

Model validation

The overtopping calculations and flood model were validated using data from the 5 December 2013 storm surge, with topography derived from immediate post-surge (January/February 2014) LiDAR imagery. This topographic data allowed the capture of the influence of the embankment breaches on the overtopping discharge into the Freshes; 13 of the 72 transects were located at breach positions. Figure 6 contrasts the maximum flood depth modelled for the 5 December 2013 storm surge with the observed flood extent derived from aerial photographs taken 4 days after the storm surge, on 9 December 2013. The model train predicts a maximum flood volume within the Freshes of 4.47 x 10^6 m^3. The modelled flood extent fits the actual flood extent well, especially given that some areas had already drained to a limited extent over this 4-day post-surge period.

Modelling the performance of the post-2013 surge embankment at Blakeney Freshes

The performance of the re-profiled embankment at Blakeney Freshes was tested under a range of scenarios. For this exercise, embankment characteristics were obtained from a LiDAR survey undertaken in November 2015 and field measured Real Time Kinetic (RTK) heights (three dimensional coordinate quality of < 50 mm, and typically < 20 mm) obtained on 29-30 December 2014. These characteristics included both the repaired embankment, where the December storm surge breaches had been infilled, and those sections of the embankment that had been re-profiled to a lower elevation than the original structure and re-graded to give a shallower gradient on the embankment sides (Figure 2d). The modelling framework was run for this new configuration, for the 5 December 2013 storm surge event and then for a series of future sea level projections applied to these 2013 storm surge characteristics.

The sea level projections were derived from climate change scenarios based on the UK Climate Projections 2018 (UKCP18) (Lowe et al., 2018; Gohar et al., 2018), which use the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) scenarios. Relative sea level rise projections for Blakeney (location: 53.03^0N 0.92^0E) were selected for RCP2.6 (Low emission), RCP4.5 (Intermediate emission) and RCP8.5 (High emission) for the years 2050 and 2100 (Table 1). To cover the full range of potential scenarios within these projections, the model output percentiles were selected as RCP2.6 5^{th} percentile, RCP4.5 50^{th} percentile, and RCP8.5 95^{th} percentile, giving a total of six future scenarios. However, the very large rise in sea level under the RCP 8.5 2100 95^{th} percentile scenario (+1.12 m), resulted in the surge and wave overtopping discharge into the Freshes exceeding the maximum volume of the site and thus this scenario was excluded from subsequent analyses. No potential changes to the offshore surge residual or wave characteristics consequent upon sea level rise were included in the modelled scenarios, in accordance with the findings of UKCP18 (Lowe et al., 2018; Gohar et al., 2018).

Results

Modelling the performance of the post-2013 repaired and re-profiled embankment at Blakeney Freshes

The maximum flood depths and extents, as applied to the new defence configuration, for the 2013 surge, and for each of the five sea level rise scenarios are presented in Figure 7. Significant flooding within the Freshes occurs in all scenarios tested, with RCP4.5 (50^{th} percentile) for 2100 having the highest maximum volume within the Freshes (5.58×10^6 m^3), whilst the 2013 storm surge scenario has the lowest volume (1.92×10^5 m^3).

In all scenarios, flood water depth is greatest on the western side of the Freshes. The overtopping calculations show that in all of the modelled scenarios the earthen embankment is overtopped predominantly along the west side of Blakeney Freshes where the embankment runs parallel to the channel between Blakeney Quay and the outer Harbour, and at the north-west margin of the site where the embankment backs an area of saltmarsh. A lower flood discharge is seen in all scenarios at the south-east side of the site next to the River Glaven. For all sea level rise scenarios, the embankment is overtopped by the subsequent tide after the initial surge, but to a much lesser extent.

The timeseries of flooded volume within the Freshes is displayed in Figure 8 for the 5 December 2013 storm surge and for this surge with 5 future sea level rise scenarios. In all cases, flood volumes show a rapid initial rise as the repaired and re-profiled embankment is overtopped, followed by slow drainage through outflow via the culverts and ground water infiltration. Blakeney Freshes supports an extensive network of creeks and channels and a significant residual volume of water can be stored in the site (88,400 m^3). This volume is that found below 1.70 m ODN; at this water level, outflow via the culverts is very low. Modelled drainage time of Blakeney Freshes to 88,400 m^3 for each of the scenarios are: 2013 surge = 2.4 days; surge + RCP2.6 (5th percentile) 2050 = 11.1 days; surge + RCP 4.5 (50th percentile) 2050 = 14.9 days; surge + RCP 2.6 (5th percentile) 2100 = 16.7 days; surge + RCP 8.5 (95th percentile) 2050 = 21.7 days; and surge + RCP 4.5 (50th percentile) 2100 which drains to creek level in 30.2 days. The relationship between the time to drain to creek level, inundation volume and the relative sea level rise for each of these scenarios is displayed in Figure 9. The time to drain shows a largely linear relationship with relative sea level rise, potentially allowing future prediction of drainage times under further sea level rise scenarios. By comparison, the maximum flood volume shows an exponential relationship with relative sea level rise.

In order to establish the potential impact of flooding on the wet grassland habitat, it is important to understand the drainage pattern of the Freshes. Figure 10a presents the area of wet grassland drained over time. The climate change scenarios exhibit a Gaussian shape, which is shifted to greater drainage time periods with an increase in relative sea level rise. In these cases the total area of the Freshes inundated is similar (~1 x 10^6 m^2). Initially, the drainage of wet grassland is low as water levels are lowered but grassland is still submerged. The rate of drainage gets faster until a peak drainage is reached, after which the rate of drainage of wet grassland falls. For all the climate change scenario cases the time at which 50% of the Freshes drains coincides with the time of peak area drained (6 days, 10 days, 12 days, 17 days and 24 days, for surge + RCPs 2.6 at 2050, 4.5 at 2050, 2.6 at 2100, 8.5 at 2050 and 4.5 at 2100 respectively). For the 2013 storm surge scenario the Freshes is flooded to a much lower inundation depth than the previously discussed scenarios and flooding occurs only on the western side, for this case the peak area drained occurs within the first day.

Discussion

In the face of increasing flood inundation due to climate change and extreme events, there is a fine balance between the viability of fixed flood defences and the expectation for total flood protection, particularly in low-lying uninhabited areas. The difference between the water volume, and flooding extent, within the Blakeney Freshes between the modelling of the actual 2013 event (i.e. with the old embankment configuration) and the modelled impact of the same event under the repaired and re-profiled embankment is considerable, being 4.47 x 10^6 m^3 v. 1.92 x 10^5 m^3 and 100 % of the vegetated area flooded v. 53.3% flooded respectively (Figures 6 and 7). These differences can be explained by the fact that the modelled 2013 flooding with the old embankment was dominated by water exchange through 13 breaches along the earthen embankment (Figures 2b-c and 6). The lower sill level at the breaches led to a negative freeboard height during the event, i.e. the still water level was above the sill level, and the flow through these breaches moved into the overflow regime. Flow through the breaches accounted for 99.5% of the modelled volume within the site during this event.

The combination of increasing sea level and maintenance of hard defences results in 'coastal squeeze' (Doody, 2004). Tidal marshes, which would typically migrate progressively landwards and upwards across the shore profile in response to sea level rise, encounter fixed barriers and are eroded. Marsh recovery is prevented, leading to further habitat loss. Thus, for example, in the Scheldt estuary, Belgium, coastal squeeze has resulted in narrower marshes, with cliffed margins fronted by non-vegetated sandflats and mudflats (Beauchard et al., 2011). By contrast, breaching, either deliberately in the case of renewing tidal exchange though managed realignment (e.g. Spencer et al., 2012), or accidentally through the unintended collapse of old and weakened embankments (e.g. French et al., 2000), leads to a sudden lateral shift, perhaps of several hundred metres, in the marsh edge from the old to the new, more landward defence line. However, this wetland extension is likely to encounter a relatively flat surface that lies below expected elevations for its position, as a result of consolidation and compaction under arable agriculture or livestock grazing and isolation from the intertidal sedimentation that has continued to characterise areas to seaward of the old defence line. Under such circumstances wetland areas may not show substantial saltmarsh re-establishment but rather reversion to mudflat (Boumans et al., 2002; Burgin, 2010).

Re-designing embankments in such a way as to prevent breaching therefore has considerable value for the maintenance of high biodiversity, ecologically-valuable embanked coastal wet grassland and reedbed, not least because such strategies 'buy' extra years of habitat protection. In this study, for example, it is not until 2100, after 0.55 m of sea level rise (i.e. under RCP 4.5 (50th percentile)), that an event with the characteristics of the December 2013 storm causes a flooding impact to the Freshes comparable to that actually experienced in 2013 (Figures 6 and 7e). This argument is, however, predicated on the long-term robustness of the repaired and re-profiled embankment which is, of course, unknown; the likelihood, and positioning of breaches is a major uncertainty in catastrophic risk modelling (e.g. Muir Wood & Bateman, 2005). The modelling framework for this study does not model morphological change or hydrodynamic forcing on the embankment, therefore it was not designed to predict the number and location of future breaches along the new defence line.

Following the storm surge of December 2013, the North Norfolk coast experienced further high magnitude storm surges on 13 January 2017 and 8 January 2019. In both events a surge coincided with a high spring tide, generating maximum still water levels at the Cromer tide gauge of 3.65 and 3.15 m ODN respectively, compared with an estimated 3.75 m ODN on 5 December 2013. Neither of these events was of sufficient magnitude to seriously test the repaired and re-profiled embankment, and both were of a lower magnitude at Blakeney than December 2013. On January 2019 peak water levels were significantly lower than in December 2013, combined with similar significant wave height (3.6 m in 01/2019, 3.8 m in

12/2013) resulted in maximum runup levels of 4.10 m ODN at Blakeney Quay, below the new embankment design height of 4.25 m ODN. The storm surge of 13 January 2017 can be considered to be a 'near miss' flood event for much of North Norfolk. At Blakeney Quay water levels reached a maximum runup elevation of 4.50 m ODN, only just exceeding the embankment design height. On 5 December 2013 they had been considerably higher, at 5.48 m ODN (Spencer et al., 2015). This difference in maximum run-up is most likely a result of the difference in wave direction between the two events (0° in 01/2017 and 340° in 12/2013). The westerly component of wave direction in 2013 allowed funnelling of water up the Blakeney Channel, as the January 2017 event had similar peak water levels to 2013 and greater significant wave height (4.4 m in 01/2017 compared with 3.8 m in 12/2013 at Blakeney Overfalls).

It is notable, however, that under every sea level scenario, even as low as 0.17 m (RCP2.6 (5th percentile) 2050), modelling predicts that the Freshes are extensively flooded under the combination of sea level rise and a 2013-type storm surge (Figure 7). Thus whilst the current embankment configuration may alleviate the likelihood of catastrophic flooding following breaching, the lower crest height does allow overtopping and thus does not remove the threat of flooding to wet grassland flora and fauna. Recent field experiments (Brotherton et al., 2019a; Brotherton et al., 2019b) have shown that intense and prolonged flooding significantly, and rapidly, affects plant distribution community composition. It has even been suggested (Casanova & Brock, 2000) that flood duration could be more important than either depth or frequency for tidal wetland plant biodiversity. For example, changes of only 10% in flood duration may be enough to eliminate some wet grassland species from flood plains (Campbell et al., 2016). In addition, it is likely that extreme flooding due to climate change will affect plant performance as well. As Brotherton et al. (2019a) field experiments have shown, plant survival is not significantly affected by flooding but species show different growth and flowering responses to the flood regimes.

Environmental modelling provides an opportunity to explore potential impacts to vegetated communities under extreme events and sea level rise scenarios, and allows coastal management strategies to be tested. Li et al. (2019) showed that a potential managed realignment at Minsmere, UK could result in the majority loss of freshwater reedbeds under even normal tidal conditions unless freshwater inputs were regulated. It is difficult to predict the precise impacts of new patterns of flooding on reedbeds and coastal wet grassland at Blakeney Freshes, given the complexities of flooding style (sudden peak v. gradual water inputs), final water depths and flood durations, and interactions between increased inundation, waterlogging and salinization (Spalding & Hester, 2007; Brotherton & Joyce, 2015). The findings of this study suggest that catastrophic loss of wet grassland from a single event by 2100 is unlikely but one might reasonably expect some re-ordering of existing plant communities (Sharpe and Baldwin, 2012). This may in turn be exacerbated by a potential increase in frequency of overtopping events as the baseline water levels increase. There is some experimental evidence for this potential re-ordering as driven by changes in inundation, albeit from freshwater wet grassland systems. For two grasses present within the Blakeney Freshes, a series of short-term experiments with variable water levels showed that the growth of both Yorkshire Fog (*Holcus lanatus*) and perennial ryegrass (*Lolium perenne*) decreased with increasing height of the water table, thought to be a response to either restricted nutrient supply and/or low oxygen levels (Watt & Haggar, 1980). This response was mirrored in a year-long experiment, where a transplantation experiment in a river floodplain showed decreases in abundance of both species when moved from a drier to a wetter site (Toogood et al., 2008). From rates of root growth in culture solutions with varying concentrations of sodium chloride, *Lolium perenne* appears less tolerant of changes in salinity than *Holcus lanatus* (Venables & Wilkins, 1978). For another grass present in the Freshes, False Oat-Grass (*Arrhenatherum elatius)*, greenhouse experiments using plants from the floodplain of the River Rhine showed this species to be highly flood intolerant, with survival rates collapsing to near zero after 10 days of submergence (Vervuren et al., 2003). Similarly, the EU RISC-KIT project (Viavattene et al., 2015) considered a threshold submergence of 10 days as being likely to trigger vegetation community change, and a threshold of 2 days to indicate changes beyond seasonal variability. Interestingly, the modelling undertaken in this study shows that for the future sea level projections applied to the 2013 storm surge characteristics over the repaired and re-profiled embankment, it is only the 2013 surge with no climate change where the majority of the Freshes' habitats flooded area is below a 2 day threshold (Figure 10b). The surge + RCP2.6 2050 scenario shows greater than 50 % of the site being inundated for between a 2 and 10 day period. The 10 day threshold for site drainage time characterises over 50 % of the site under surge + RCP4.5 at 2050 and surge + RCP2.6 at 2100 and almost the entire site under surge + RCP4.5 at 2100 and surge + RCP8.5 at 2050 (Figure 10b). Finally, the Rhine study also showed that another Blakeney species, Curled dock (*Rumex crispus*), is highly flood tolerant, with survival rates only declining after a minimum of 50 days submergence, and often only after more than 100 days of flooding (Vervuren et al., 2003 (and see also Blom et al., 1994)), suggesting that *Rumex* might outcompete *Arrhenatherum* under a changed flooding regime.

Clearly, however, these relationships are likely to be further modified by the fact that the inundations are of saline water, highlighting the growing threat to wet grasslands of increased salinization in general (Herbert et al., 2015). At Blakeney Freshes, salinization might affect the relative coverage of reedbeds and coastal wet grassland. Experimentation by Lissner & Schierup (1997) showed that growth rates of *Phragmites australis* were optimized at 5% salinity but with 100% mortality by 35 ‰; die-back took place when soil water salinities were >15‰ in the rooting zone. These effects can be prolonged. In a separate experiment, flooding of a cut *Phragmites* stubble with brackish water resulted in no further above-ground growth for 18 months (Hellings & Gallagher, 1992). However, in a combined salinity and inundation experiment, biomass production was stimulated in the grass creeping bent (*Agrostis stolonifera*) by flooding but depressed in the saltmarsh rush

(*Juncus gerardii*). Addition of seawater markedly depressed the growth of *Agrostis* stolonifera, whereas that of *Juncus* was not significantly changed (Rozema & Blom, 1977). These findings suggest that salinization at Blakeney Freshes may result in vegetation community change.

Conclusions

As sea level rise accelerates, habitats formed through reclamation of low-lying coastal areas are increasingly under threat. Reclaimed wetland environments are now highly valued, as attested by nationally and regionally recognised protected status. Arising from extensive reclamation during the seventeenth century, Blakeney Freshes epitomises the challenge of maintaining the viability of coastal wet grassland with uncertain climate change and within the bounds of financial feasibility and political acceptability. The modelling performed here reveals a degree of inevitability regarding future flooding of wet grassland and the presence of trade-offs between catastrophic flooding events and more frequent inundation.

In the first instance, it is clear that the breaching of defences which enclose wet grassland habitats represents a catastrophic impact. Although inundation depths and drainage times increase as sea levels rise, it is not until 2100 (under surge + RCP4.5 (50^{th} percentile) = +0.55 m of sea level rise) that flooding through overtopping the reprofiled embankment results in inundation depths comparable to the breach-induced flooding of 2013. Preventing breaching remains, therefore, a key objective (and uncertainty) in the maintenance of such defences. A proven approach for achieving this aim is the lowering and widening of embankments. This involves a decision regarding the height of the reprofiled embankment, which has a direct bearing on the overtopping volume during subsequent extreme water level events. Despite an uncertain future, we have shown that information on event frequency, severity, and vegetation resilience to inundation are necessary to make an informed decision about embankment height and therefore amount of overtopping that is permitted. The amount of overtopping that is deemed optimum will also depend on the perceived value of flood storage during extreme water level events and therefore the value of property that is not flooded as a result of wet grassland inundation.

Extensive flooding of the Freshes, as modelled, occurs under every sea level rise scenario when combined with a 5 December 2013 type surge event. Assuming that one of the goals of embankment lowering is to facilitate survival of the enclosed wetland habitat (in addition to the flood water storage) then an understanding of vegetation resilience to inundation frequency and duration is critical. At present there is very limited data for survival rates of plant species typical of coastal wet grassland in response to saline water inundation. This makes it difficult to establish thresholds beyond which vegetation recovery is unlikely. The threshold value of 10 days used here highlights a threshold of expected vegetation community change. The exact nature of this change on an individual plant level will likely vary according to numerous factors including species, plant maturity, and both antecedent and post-storm conditions (e.g. the occurrence of rainfall which might have a freshening effect). Establishing baseline datasets to quantify vegetation responses to inundation driven disruptions should be a future research priority.

Over the last couple of decades, thinking about the potential impacts of climate change on tidal wetland restoration has evolved from a general awareness to a central focus in the design of ecological engineering projects, especially on the long-term sustainability of restored tidal wetlands (Parker et al., 2012). In this sense, restoration has become much more focused on creating conditions that will develop sustainable and resilient plant communities rather than designing specific historical communities for restoration projects (Critchley et al., 2003; Toogood and Joyce, 2009; Palaima, 2012; Smith & Medeiros, 2013; Hayes et al., 2015). Our results have direct implications for ecological engineering and the maintenance of tidal wetland plant communities' characterised by high biodiversity/resilience to the more frequent inundation effects caused by global warming. Coastal wetlands should be able to sustain vegetation under the flooding extremes induced by climate change but community composition, biodiversity, and wetland services are all likely to be affected by such changing environmental dynamics.

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List of Tables

Table 1. Relative sea level rise projections with probabilistic model output percentiles for Blakeney Freshes (53.03^0N 0.92^0E) from UKCP18 (Lowe et al., 2018; Gohar et al., 2018). Sea level rise projections are relative to a 1981-2000 baseline period.

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	Relative sea level rise (m)	
Scenario	**2050**	**2100**
RCP 2.6 (5th percentile)	0.17	0.30
RCP 4.5 (50th percentile)	0.26	0.55
RCP 8.5 (95th percentile)	0.40	1.12

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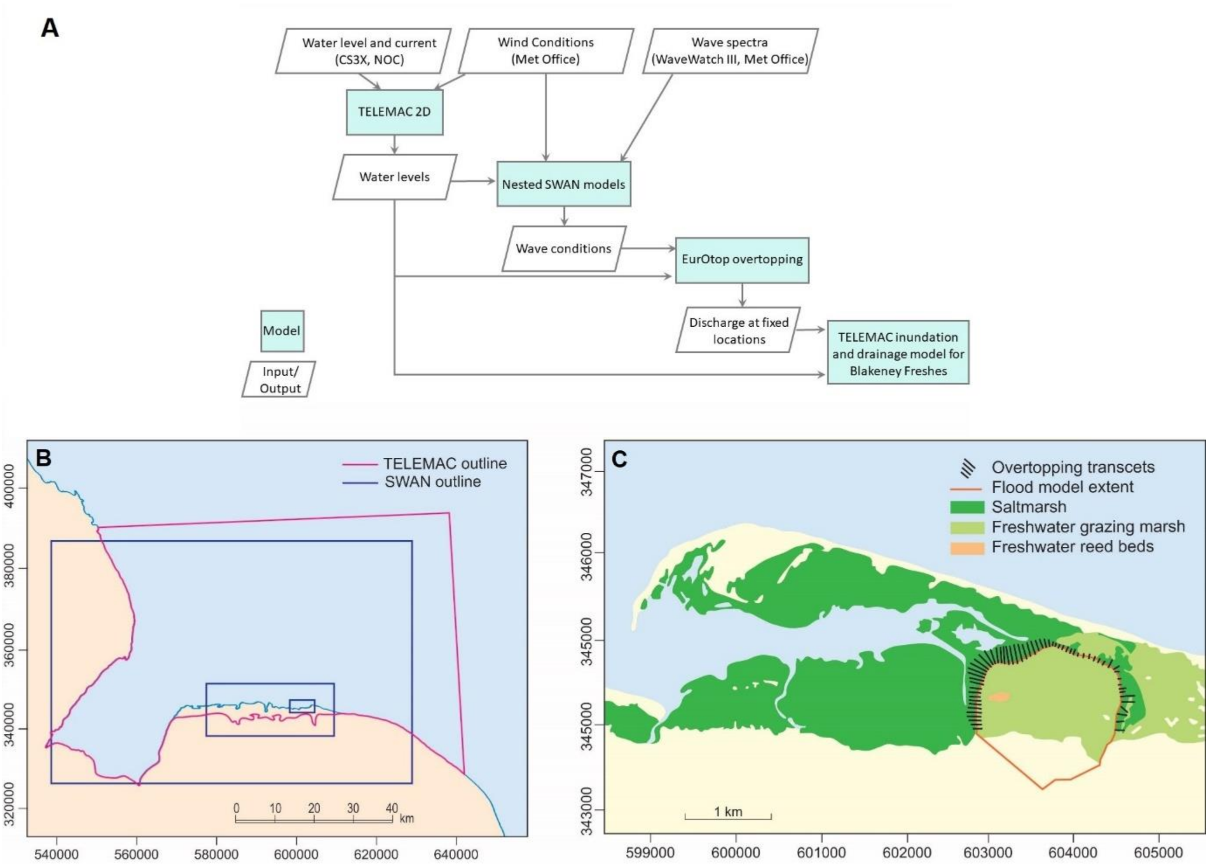

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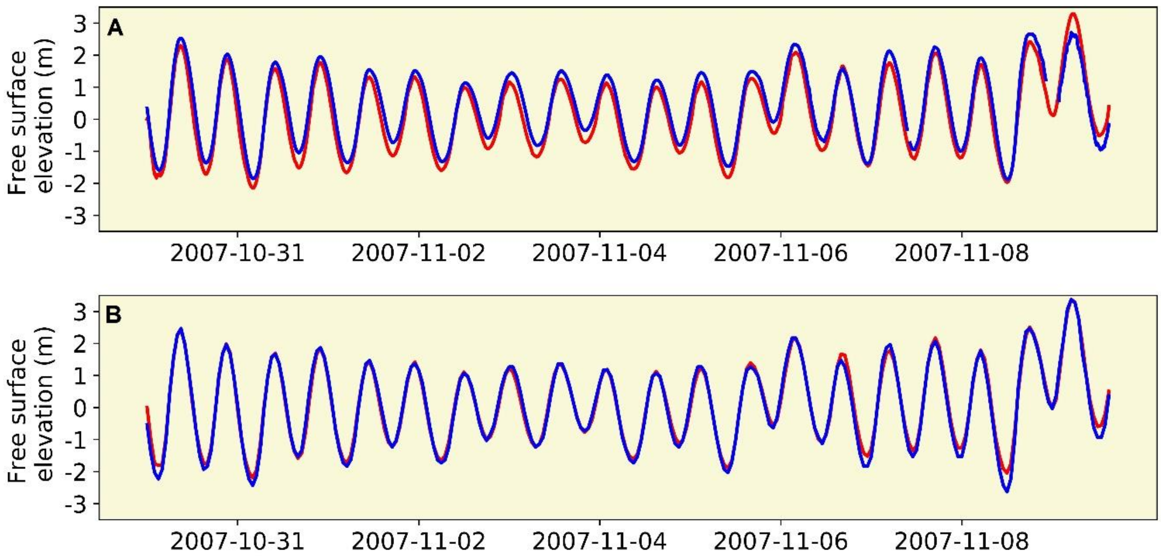

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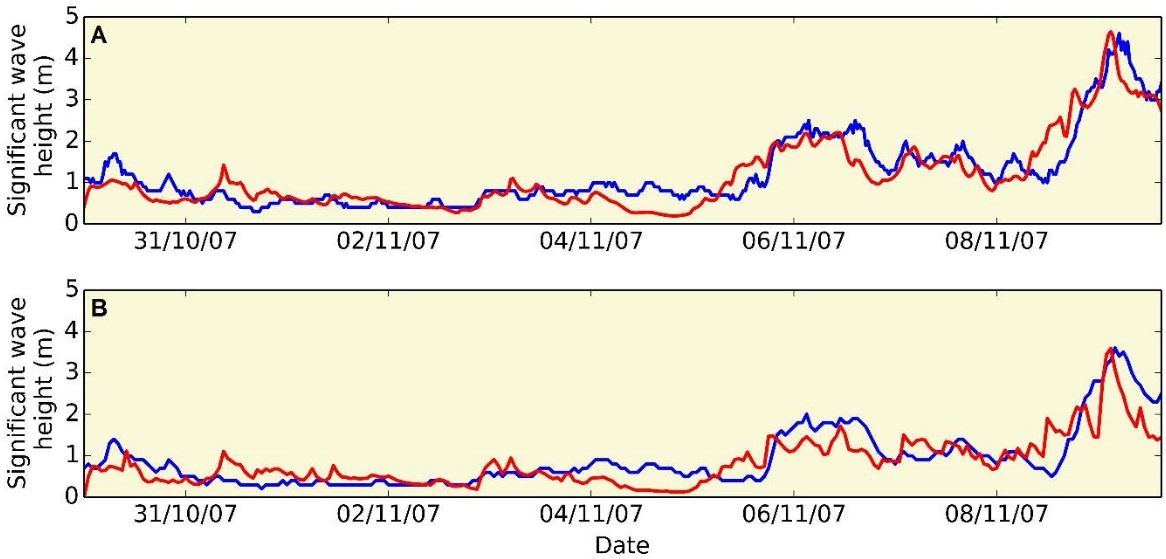

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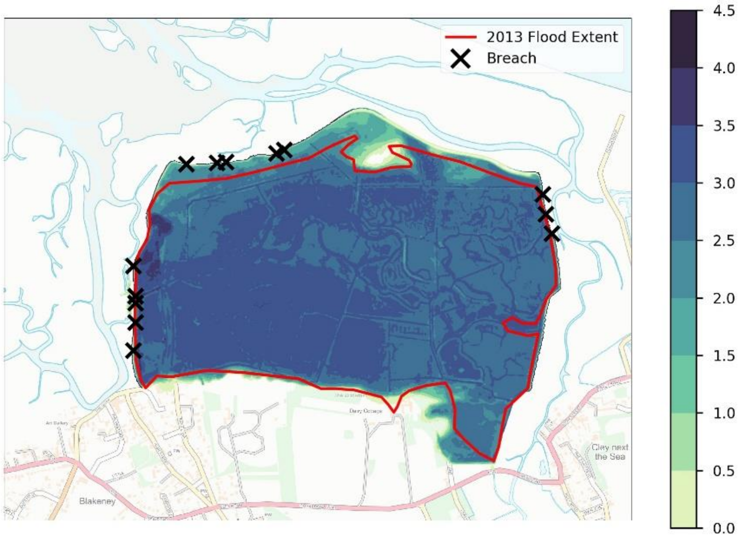

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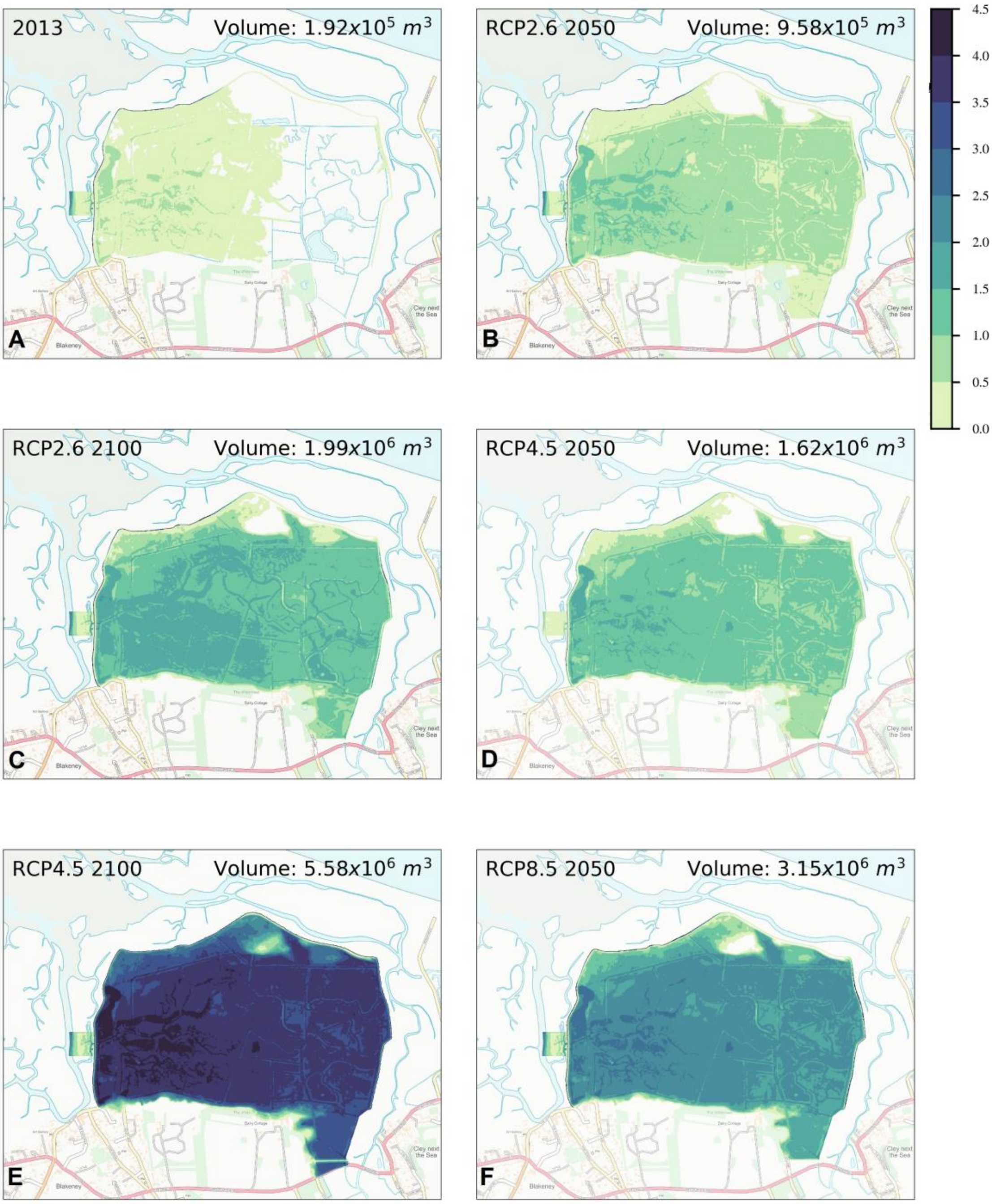

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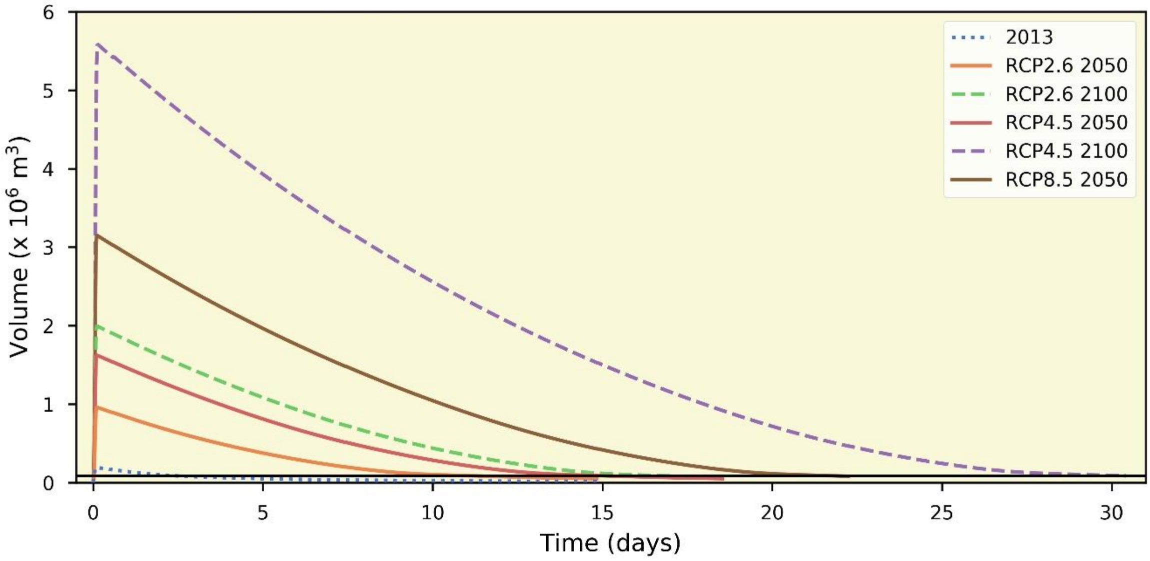

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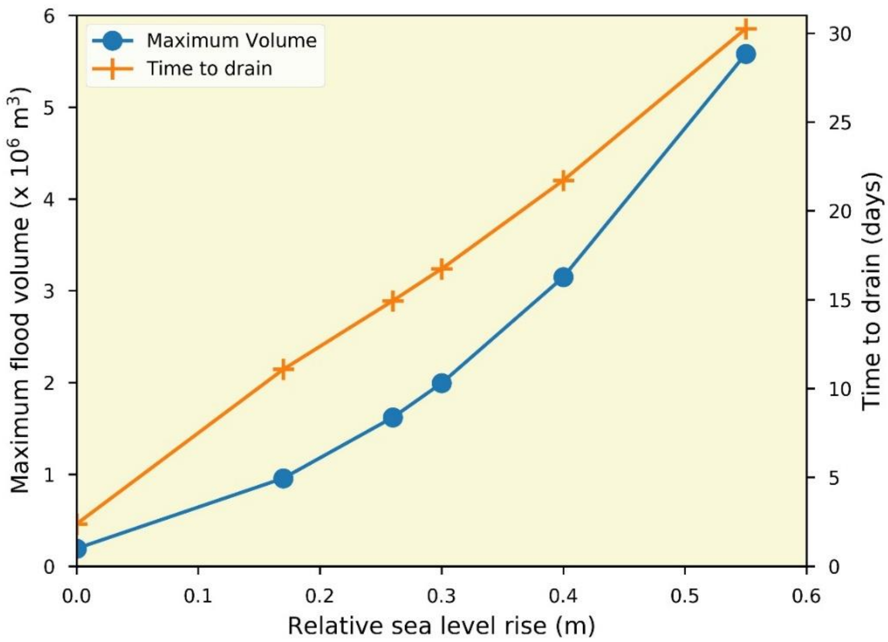

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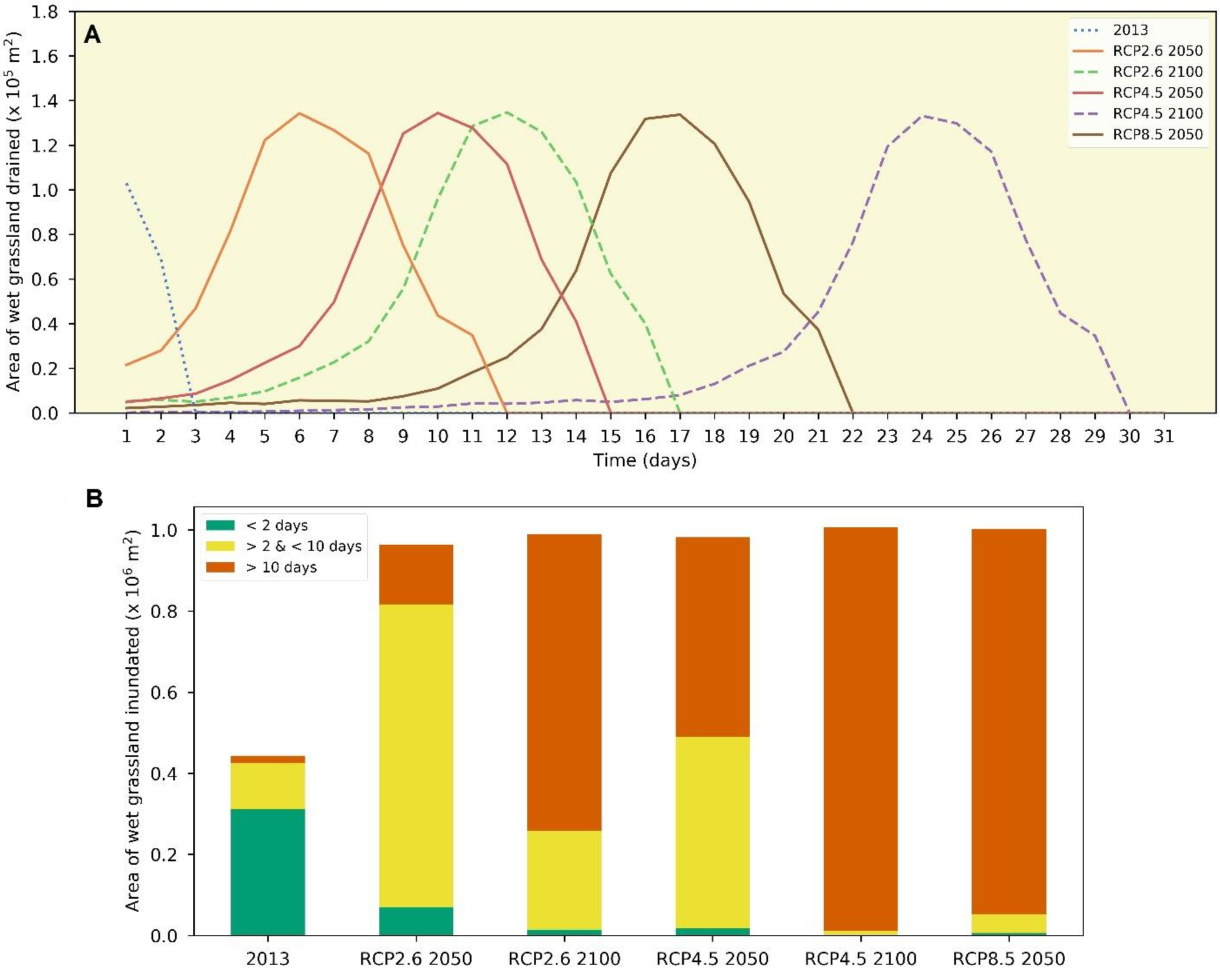

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