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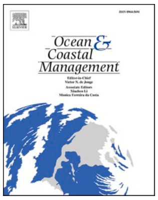

Unmanaged realignment: Recent examples and the morphological evolution of naturally breached flood defences

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ABSTRACT

Managed realignment describes the breaching of coastal flood defence such as sea walls, embankments, and barrier beaches for habitat restoration and flood defence purposes. These sites are deliberately breached at pre-determined locations, often with extensive engineering works carried out to encourage a mosaic of habitat types. However, landscaping and engineering works typically alter the site's morphology, resulting in a more simplified creek and drainage network with lower topographic variability than natural saltmarshes. As a result, drainage might be restricted, impacting the plant communities that can colonise and preventing widespread sedimentation and seed dispersal. In contrast, unmanaged realignment (uMR) is the natural breaching of flood defences without any of these costly engineering or landscaping works performed prior to site breaching. uMR sites provide an opportunity to assess the 'natural' morphological evolution of realignment sites without the influence of extensive site design, engineering, or landscaping features, yet there remains little analysis of the evolution of 'recent' uMR sites. To address this gap in knowledge, this paper describes ten recent occurrences of uMR on the coast of England since 1996. From these sites, five were selected for analysis of the pre-breach morphology in comparison to areas of natural saltmarsh and the subsequent morphological evolution. In general, lower topographic variability, although a higher density of creeks, was found within the sites before breaching in comparison to the adjacent areas of natural marsh. Following site breaching, results suggest that uMR sites become less topographically diverse, with some evidence of subsequent increases in topographic variability at the two oldest uMR sites. Findings are discussed in terms of the potential benefits of uMR for shoreline management planning. It is recommended that further consideration of the wider impact of uMR on coastal and estuarine systems is required within the shoreline management process to ensure uMR sites have a positive impact on the strategic delivery of shoreline management planning.

1. Introduction

Intertidal habitats, such as saltmarsh, provide a range of ecosystem services including carbon storage, water quality regulation and habitats for juvenile fish species (Barbier et al., 2011), but are vulnerable to erosion caused by climate change and sea level rise (Burden et al., 2020). Intertidal habitats could be maintained through the landward migration of saltmarsh, however this is only possible where there are no defences behind the saltmarsh which would otherwise prevent landwards movement; a process known as coastal squeeze (e.g. Doody, 2004). Historically, reclamation of low-lying areas of the coastline has reduced the extent of mudflat and saltmarsh. Sea walls and embankments constructed as part of this reclamation have long defended land now used for arable or intensively managed grassland, grazing land, brackish and freshwater wetlands and marshes. Often these areas are lower in elevation when compared to the current tidal frame because of shrinkage and dewatering, sediment starvation and rising sea level, although some still exhibit their previous estuarine influence through relic intertidal creek patterns.

In England, and elsewhere in Europe (e.g. Rupp-Armstrong and Nicholls, 2007), managed realignment (MR) has been used to allow inland migration of saltmarsh and compensate for losses elsewhere through breaching, removing or lowering coastal flood defences. The first MR in England was undertaken at Northey Island on Blackwater Estuary in 1991 (Wolters et al., 2005). Since then, approximately 54 MR sites have been implemented around the UK's coast (ABPmer Online

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Marine Registry, 2022). Predominantly, realignments have occurred within estuarine environments, although several MR sites have also been constructed on the open coast. For example, the breach at Medmerry, West Sussex was artificially cut through a gravel barrier beach to allow a range of intertidal habitats to develop landwards (e.g. Dale et al., 2018).

Despite MR being implemented in order to restore and compensate for saltmarsh habitat loss, evidence suggests that MR sites have a lower abundance and diversity of key species, and a high percentage of bare ground (Mossman et al., 2012) in comparison to natural saltmarsh. This is not to mean that MR sites are un-natural, rather they suffer from reduced subsurface hydro-connectivity, lower topographic variability, and poor drainage (Lawrence et al., 2018; Spencer et al., 2017). The design of drainage features within MR usually involves the use of constructed channels and existing (terrestrial) drainage ditches, rather than relic intertidal creeks. As a result, the morphology of MR sites is often closer to that of a terrestrial field than saltmarsh (Lawrence et al., 2018), which may result in not only restricted drainage but prevent the dispersal of seeds and restrict plant colonisation. Furthermore, constructed site design features may influence the movement of sediment within MR sites, meaning any post site breaching morphological development may not be representative of 'natural' evolution following the introduction of intertidal conditions and further restrict site colonisation. However, little is known of the temporal variability in the topographic and morphological evolution of MR sites as a result of the site design and construction process.

One type of realignment where landscaping typically does not take place is unmanaged realignment (uMR). Whilst there are established definitions of what MR involves (Esteves, 2014; Leggett et al., 2004), this is not the case for uMR with several varying definitions existing (Table 1). Initially Burd (1992) identified these sites as experiencing 'historical sea defence failure', whereas more recently Burden et al. (2020) use the term 'accidental breaching' to describe sites where breaching has occurred during storms. Although many uMR sites form because of defence failure during a storm event, given the movement towards policies of no active intervention within shoreline management plans, uMR arguably should not be viewed as an "accident" or an "abandonment" of coastal management. The term non-engineered managed realignment was proposed by Dale et al. (2021), however in some case engineering works may still be required post site breaching such as the construction of new inland defences or relocation of infrastructure. We, therefore, propose the use of the term unmanaged realignment to describe sites which have breached and been allowed to develop naturally. In our definition *breach* is taken to mean a failure of a coastal flood defence structure allowing flooding through tidal water exchange for at least half of the tidal cycle, i.e. the level of the breach is visibly at or below mean sea level. *Naturally* is taken to mean that no engineering works or landscaping have been undertaken to either breach the site artificially or to alter the site significantly to result in inundation, or to the morphology within the site.

In addition to a lack of definition regarding what uMR involves, these sites receive considerably less scientific attention and funding in comparison to MR. This is partially due to the extensive monitoring programmes carried out at MR sites, due to the need to quantify and qualify the delivery of the specific design requirements of each scheme. To date uMR sites have received only limited scientific attention, with most work focusing on historical sea defence failure (e.g. Burd, 1992; Cundy et al., 2002). Whilst examining these sites provides useful analogues for evaluating the potential longer-term colonisation and development of both MR and uMR sites (e.g. Garbutt and Wolters, 2008), they do not provide empirical evidence of the influence pre-site breaching conditions (managed or unmanaged) have on site evolution. Dale et al. (2021) did provide an assessment of changes in morphology in a modern uMR site at Cwm Ivy Marsh, Gower Peninsular, Wales through repeat topography surveys using an Unmanned Aerial System. However, the data used by these authors did not include a survey before site breaching, and only considered one site which may not be representative of the typical evolution of uMR sites. Furthermore, there remains a lack of detailed investigation into uMR sites on the English coast, where both MR and uMR sites are more common but more variable in terms of size, tidal range, sediment supply and location within estuaries. This paper aims to address this knowledge gap by providing a description of recent uMR sites in England, and their morphological evolution. Specifically, we evaluate:

i. The occurrence of recent examples of uMR in England
ii. The morphological difference between uMR sites and areas of natural saltmarsh, and the subsequent morphological evolution of uMR sites.
iii. The potential to implement uMR into shoreline management planning in response to habitat loss and a need for improved coastal flood defence because of sea level rise and predicted increases in storm magnitude and frequency.

Table 1
Terms used to describe realignment of the coast that is not managed in England.

Term	Source
Historical sea defence failure	Burd (1992)
Abandoned reclamations	French et al. (2000)
Natural breaching	Wolters et al. (2005)
Natural storm breaching	French (2006)
Catastrophic realignment	Pontee (2007)
Natural realignment	Pontee (2007)
Controlled abandonment	Adnitt et al. (2007)
Do-nothing	Adnitt et al. (2007)
Abandoned reclamations	Garbutt and Wolters (2008)
Accidental breaching	Burden et al. (2020)
Non-engineered managed realignment	Dale et al. (2021)
Unmanaged Realignment	ABPmer Online Marine Registry (2022)

2. Methods

2.1. Recent examples of unmanaged realignment sites

An extensive literature review was conducted (via Google, Google Scholar, Science Direct) using the terms used to describe uMR outlined in Table 1. In addition, sites were identified through communication with practitioners who have visited, managed, or provided advice on the sites, resulting in the identification of ten recent uMR sites (Fig. 1, summarised in Table 2).

2.1.1. Porlock, Somerset (1996)

The oldest, and only open coast, uMR site considered here is Porlock, Somerset. The 75 ha site formed following a storm, the remnant of Hurricane Lili, on 28th to 29th October 1996 (Orford et al., 2003). The storm created a permanent breach in the shingle barrier beach, which subsequently widened and deepened, allowing an annual rate of around 20 mm/yr of sediment to be deposited in the first four years of site inundation (Bray and Duane, 2001). As a result of the exposure to intertidal conditions, extensive areas of lower (37ha) and mid (2ha) saltmarsh developed within a year of site breaching. Porlock is now part of Porlock Ridge and Saltmarsh Site of Special Scientific Interest (SSSI) which includes the gravel barrier beach and the back barrier floodplain (formerly Porlock Marsh SSSI from 1990 until 2002).

2.1.2. Great Orcheton Fields, Erme Estuary, Devon (2007)

Great Orcheton Fields is part of the upper Erme Estuary, Devon, a macro-tidal estuary on the south coast of England. In December 2007, extreme high tides occurred in the estuary as a south westerly storm surge coincided with sustained rainfall, resulting in a breach in the wall on the eastern side of the estuary. There had been two previous failures of the sea wall but, following a third and final breach in the south-western corner of the site, the landowner decided to 'work with nature' and entered into an Environmental Stewardship agreement with Natural

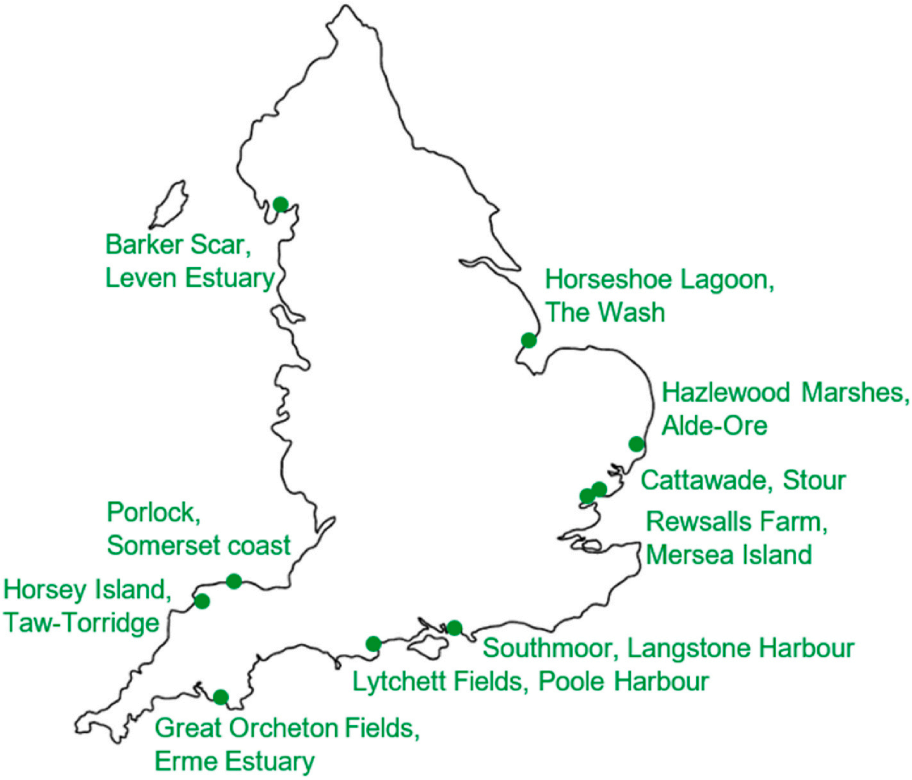

Fig. 1. Recent unmanaged realignment (uMR) sites in England.

Table 2
Recent unmanaged realignment (uMR) sites in England and distance to natural reference marshes for site selected for morphological analysis.

Name	Year Breached	Size (ha)	Estuary/ Coastal System	Distance to natural reference marsh (m)
Porlock	1996	75	Bristol Channel	–
Great Orcheton Fields	2007	24	Erme Estuary	660
Barker Scar	c. 2011	23	Leven Estuary	–
Lytchett Fields	2012	23	Poole Harbour	–
Hazlewood Marshes	2013	64	Alde-Ore Estuary	450
Horseshoe Lagoon	2013	8	The Wash	–
Cattawade	2016	7	Stour Estuary	560
Horsey Island	2017	87	Taw-Torridge Estuary	800
Southmoor	2020	8.8	Langstone Harbour	450
Rawsalls Farm	2021	17.5	Colne Estuary	–

England (a public body, established in 2006, to advise the UK government on the natural environment in England). This land management agreement supported the maintenance of the site as intertidal habitat. The 24 ha site has a full mix of transitional coastal habitats from bare sand at the breach through areas of mud and marsh in the middle of the site up to grassland in the upper reaches (ABPmer Online Marine Registry, 2022).

2.1.3. *Barker Scar, Leven Estuary, Cumbria (c. 2011)*

Barker Scar is sheltered within the upper Leven estuary in Morecambe Bay, a macro-tidal estuary in the northwest of England. Previously an embankment provided flood protection to the reclaimed land behind. It is likely that the integrity of the estuary facing embankment continuously weakened before failure, inundating grazing land behind. From observations, the front face of the wall has continued to erode, while a tidal channel to the south of the site has widened. This has created 23 ha of upper saltmarsh and transitional grassland. It is adjacent on its western boundary to the Morecambe Bay SSSI.

2.1.4. *Lytchett Fields, Poole Harbour, Dorset (2012)*

Lytchett Fields, a site within Poole Harbour in Dorset, southern England, formed in late 2012 via two small breaches to the embankment which were not repaired. The majority of the 23 ha site consists of wet tidal mud and grassland, with some areas of reedbed. The site is relatively low-lying throughout and would once have been part of the marshes fringing the micro-tidal harbour, but was separated for many years from the harbour and a harbour tributary, the Sherford River, by an artificial embankment. In January 2019 the Poole Harbour SSSI was extended to include Lytchett Fields as well as subtidal areas of Poole Harbour.

2.1.5. *Hazlewood Marshes, Alde-Ore Estuary, Suffolk (2013)*

Following the tidal surge from Storm Xaver on 5th December 2013 (e.g. Spencer et al., 2015), a sea wall on the meso-tidal Alde Estuary was breached initially in two places at Hazlewood Marshes. The site is within the Alde-Ore Estuary SSSI, and most of the site is owned and managed by the Suffolk Wildlife Trust for its freshwater and terrestrial interest including freshwater marsh and discrete areas of reedbed. The two breaches occurred on lower sections of defence and have resulted in a change of habitat types to intertidal mudflat and saltmarsh. After breaching it was acknowledged that it was unsustainable to continue maintaining the sea wall that protected the freshwater and terrestrial habitats of Hazlewood Marshes, therefore the breaches were not repaired. The breach has resulted in the development of 64 ha of intertidal habitat. The site was initially larger but private investment was used to build a counter wall through part (3.3ha) of its southeast corner.

2.1.6. *Horseshoe Lagoon, the Wash, Lincolnshire (2013)*

Horseshoe Lagoon is located on the north-west side of The Wash macro-tidal embayment on the east coast of England. There are three lines of sea defence which provide flood protection along the northern bank, furthest seaward is a 1977 privately owned earth embankment known as 'Jubilee Bank', which has reclaimed the previous intertidal behind. As a result of the tidal surge from Storm Xaver on 5th December 2013 (e.g. Spencer et al., 2015) the embankment breached in two places resulting agricultural land being flooded. The two adjacent breaches were estimated at the time as having widths approximately 30 m and 40 m at the top of the bank (Environment Agency, 2014). Flood water after the 5th-7th December was unable to fully drain due to the reclaimed land decreasing in elevation through compaction and dewatering, resulting in the flood water having to be pumped out. In reaction to the breach the private landowner used a temporary defence solution to prevent further flooding and potential widening of the breaches. A new counter wall, known as Wrangle Bank, was built landwards by the Internal Drainage Board (a public body managing local water levels) and local stakeholders, cutting off the flood route out of the 'lagoon', with a culvert installed in the southernly corner of the site for drainage. Tidal waters now enter and exit the site, which is almost 8 ha in size, via this culvert resulting in a microtidal range (author's unpublished data).

2.1.7. Cattawade, Stour Estuary, Essex (2016)

Following sluice failure, intertidal habitat has formed in approximately 7 ha of former grazing grass land at Cattawade, in the upper reach of the Stour Estuary, east coast of England. Whilst a breach initially developed in 2016 at the location where water historically drained from the site, a secondary beach has developed in 2017/18 close to this location. Following inundation, the terrestrial vegetation has died back, and mudflat is developing rapidly. The site is bound to the north by a road, to the south by a railway embankment and flanked on both sides by the Stour Estuary SSSI. As the site is privately owned, there is no guarantee it will remain as a uMR and could be reversed.

2.1.8. Horsey Island, Taw-Torridge Estuary, Devon (2017)

Located on the northern bank of the Taw estuary, on the west coast of England, Horsey Island breached in November 2017 due to the sea wall failing. Initially, private works were carried out to repair the sea wall, however these were never completed. A range of mudflat and saltmarsh habitats are found within the 87 ha site, which had been previously reclaimed in 1853, had been identified as a potential site for managed realignment (Davis et al., 2019). As a result of site breaching, it has been suggested that the tidal volume of the estuary may increase, and therefore a corresponding increase in estuary width is expected; Pethick (2007) estimated that the width at the mouth of the estuary, between Northam Burrows and Braunton Burrows, will increase by 33 m and the tidal volume of the estuary would increase by over 1.5 million m^3 (or 2.9%) as a result of the breach to Horsey Island. The extent of any changes at the mouth of the estuary following site breaching has not, however, been investigated.

2.1.9. Southmoor, Langstone Harbour, Hampshire (2020)

Southmoor is an 8.8 ha site located at the top of Langstone Harbour in the Solent, Southern England, and breached on 22nd September 2020. A privately-owned sea wall fronts the site and provides defence against tidal flooding from the harbour. The site had previously been identified as a location where managed realignment may be possible (Bray and Cottle, 2003). However, the managed realignment was not carried out due to excessive costs of the project, which were predominantly the result of adjustments required to the utility supplies and facilities within the site prior to site breaching (pers.comms. UK Environment Agency).

2.1.10. Rawsalls Farm, Colne Estuary, Essex (2021)

Rewsalls Farm is a 17.5 ha site, located on the Colne Estuary in Essex. The breach occurred in February 2021 where a low earth embankment was overtopped and subsequently created a full tidal exchange at the south eastern edge of the site. The extent of the site is limited by a secondary defence.

2.2. Morphological change in unmanaged realignment sites

Five of the uMR sites identified were selected for analysis of the morphological evolution following site breaching: Great Orcheton Fields, Hazlewood Marshes, Cattawade, Horsey Island and Southmoor (Fig. 2). Sites were selected on the basis that they are currently under-researched (no known research projects have been or are being conducted at these sites) and on data availability, ensuring a range of different uMR sites (tidal range, position in estuary, nature of breach) were included. Digital Terrain Models (DTMs) with a 1 m pixel resolution were downloaded from the UK Environment Agency National LiDAR (Light Detecting and Ranging) Programme (https://www.data.gov.uk/dataset/f0db0249-f17b-4036-9e65-309148c97ce4/national-lidar-programme) on 22nd November 2022. To evaluate the extent to which each site's pre-breach morphology was representative of a saltmarsh environment, elevation data were extracted from DTMs collected prior to site breaching from the uMR site and compared to the nearest downstream area of adjacent natural saltmarsh (Table 2). The subsequent morphological development was then assessed for the uMR in the years following site breaching.

In all instances morphology was represented by the rugosity, a measure of the topographic variability calculated from the standard deviation of the elevation of a 3 m × 3 m moving grid (Lawrence et al., 2018), and inverse Strahler stream order analysis (Chirol et al., 2018; Strahler, 1957) from which the creek density (m per ha) was calculated. As data were not normally distributed (Anderson-Darling, $p < 0.05$), a Mann-Whitney *U* test was used to assess if the overall difference in rugosity and total creek density between the uMR prior to site breaching and natural saltmarsh was significantly different. The association between time and the number of creeks in each order was assessed for each site using Chi^2 analysis. All analysis was conducted using ArcMap (v10.5.1) and Minitab (v21) and all statistical tests were conducted using a confidence level of 95%.

3. Results

Comparisons between each of the five uMR sites and adjacent areas of natural saltmarsh, and changes in morphology in the uMR following site inundation, are presented in Table 3. Except for Southmoor, rugosity measurements indicated the pre-breach topography (mean = 0.05 ± 0.01) was less variable than the natural marsh (mean = 0.07 ± 0.02) although this difference, albeit with a small sample size, was not statistically significant. An average higher creek density was also detected in the uMR sites (mean = 394 m/ha) prior to breaching compared to the natural marshes (mean = 325 m/ha); the only site where creek density was higher in the natural marsh was Great Orcheton Fields. However, the difference in creek densities between the natural saltmarsh and uMR site before site breaching was not statistically significant, although it should be acknowledged that the small sample size may have contributed toward this result.

At Great Orcheton Fields, despite an initial decrease, creek density increased following site breaching. Prior to site breaching, and in the first year afterwards, three creek orders were detected, increasing to four orders three years after the site breached. Chi^2 analysis indicated a significant association between the number of creeks in each order and time ($p < 0.01$). In contrast, at Hazlewood Marshes, creeks were divided into five orders pre- and post-breach with the creek density demonstrating less change, although creek density did initially decrease before returning to a density similar to before site breaching. An association was, however, found at Hazlewood Marshes between the number of creeks in each order and time ($p = 0.03$). Rugosity increased from 0.03 to 0.04 following breaching.

Following site breaching at Cattawade, the density of creeks decreased following breaching, with a statistically significant

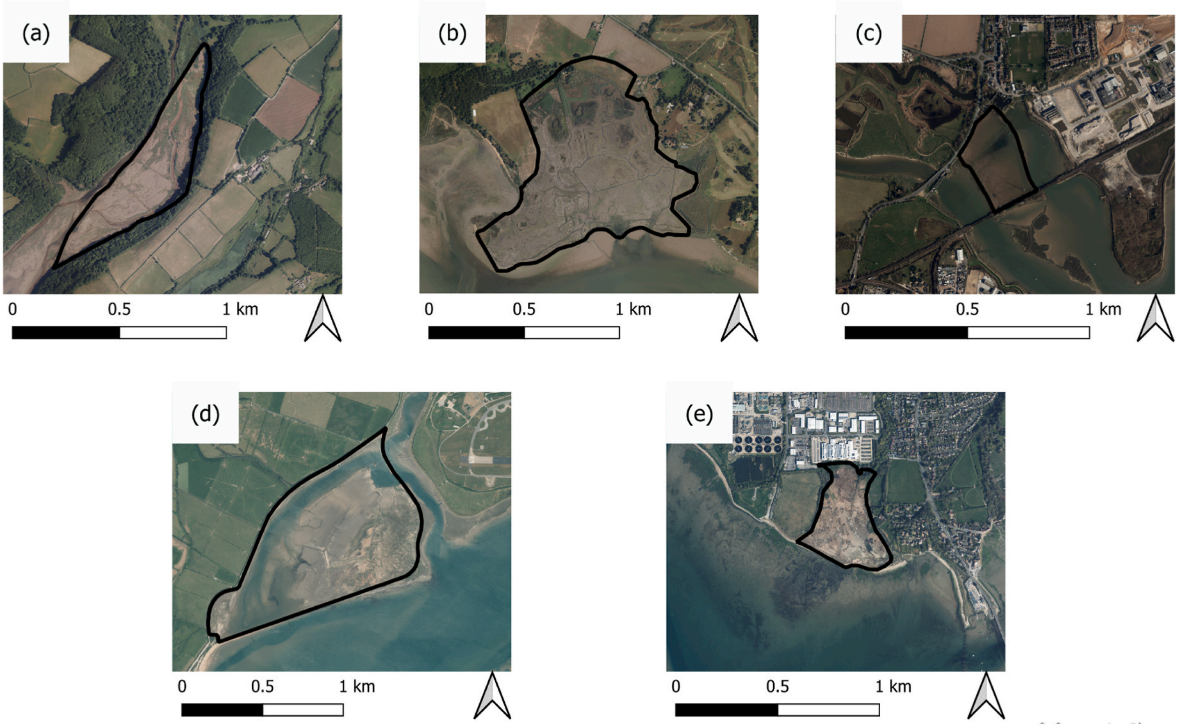

Fig. 2. The five unmanaged realignment sites selected for morphological analysis: (a) Great Orcheton Fields, (b) Hazlewood Marshes, (c) Cattawade, (d) Horsey Island and (c) Southmoor (EDINA Aerial Digimap Service, https://digimap.edina.ac.uk, © Getmapping Plc).

association ($p < 0.01$) being found between the number of creeks in each order and time. However, the number of creek orders increased from five orders, detected both before and one year after site breaching, to six orders after four years of inundation. A decreased from 0.06 to 0.05 was observed in rugosity. At Horsey Island an initial decrease, but little overall change, in creek density was detected. Five creek orders were identified throughout, although the number of creeks in each order did change and was found to be associated with time ($p < 0.01$). Rugosity decreased from 0.05 to 0.04 at this site. At Southmoor, one of the most recent uMR sites included in this study, rugosity remained constant following site breaching although only a slight decrease in creek density was detected. Three creek orders were identified, but no association was found between number of creeks per order and time.

4. Discussion

A total of ten uMR sites in England have been described, equating to approximately 338 ha of habitat recovery. However, Porlock, Hazlewood Marsh, and Horsey Island, the largest of the uMR sites described herein (all over 60 ha), are relatively small compared to the largest MR schemes such as Alkborough (Wheeler et al., 2008) and Medmerry (e.g. Dale, 2018), both of which are over 300ha. The cumulative area (ha) of uMR illustrates an exponential trend (Fig. 3), with six of the most recent uMR occurring during the last ten years.

4.1. *The morphological evolution of recent unmanaged realignments*

Although the overall difference in rugosity between the uMR sites before breaching and the natural saltmarshes was not statistically significant, topography was found to be more variable in the natural saltmarsh, with a similar trend detected by Lawrence et al. (2018). Following site breaching, rugosity increased at two of the five sites (Great Orcheton Fields and Hazlewood Marshes), matching the evolution a near breach site within the Medmerry MR site (Dale et al., 2020). However, rugosity decreased at Cattawade and Horsey Island, which is consistent with observations made at the Cwm Ivy Marsh uMR site by Dale et al. (2021). It uncertain why these sites followed a different trend following site breaching, although there are similarities between Horsey Island and Cwm Ivy; both are a similar size and located on the Bristol Channel, and therefore have a large tidal range and readily available sediment supply which could rework material within the site and/or rapidly bury the pre-breach topographic features. Furthermore, post breach rugosity values remained below the measured topography variability in the natural marshes at all sites except for Southmoor. However, Southmoor is situated in Langstone Harbour which has experienced considerable levels of saltmarsh loss and fragmentation, resulting in the marshes in the harbour breaking up and becoming less complex (Baily and Pearson, 2007). These findings highlight the importance of evaluating the condition of natural marshes and assessing any influence on comparisons between natural and restored saltmarshes.

At all sites considered in this study, creek networks were not constructed, engineered, or landscaped prior to site breaching, with the drainage networks in each site left to become established via the pre-existing drainage features. Initially, prior to site breaching, all sites apart from Great Orcheton Fields had a higher creek density than the natural reference marshes. However, at all sites creek density initially decreased, matching observations made during other temporal studies of the evolution of MR sites (Dale et al., 2020, 2021). Creek density subsequently increased at the older sites, indicative of some of the channel networks becoming more dominant and then developing, with other channels infilling as the volume of water and frequency of use decreased (Dale et al., 2020). Functioning drainage networks that act as a conduit for water, sediment, seeds, and nutrients are essential for site development. Whilst these results indicate that the drainage networks in uMR sites only utilise part of the available pre-existing network of channels, this can still be considered morphological evolution and represents the site developing a channel network away from the influence of pre-breach drainage features.

Previous studies conducted at MR sites have identified that pre-existing features, such as plough lines, can have a major impact on creek development and in some cases become permanent features (Bowron et al., 2011; French and Stoddart, 1992). It is likely that the

Table 3
Topographic properties (rugosity, number of creeks and creek density) before and in subsequent years after site breaching for each unmanaged realignment site and the adjacent natural reference marsh sites considered in this study.

		Number of Creeks								Creek Density (m/ha)						
		Rugosity	1st Order	2nd Order	3rd Order	4th Order	5th Order	6th Order	Total	1st Order	2nd Order	3rd Order	4th Order	5th Order	6th Order	Total
Great Orcheton Fields	Natural	0.09	10	23					33	360	124					360
	Pre-breach	0.06	20	28	59				107	52	53	155				260
	Breach +1 Year	0.05	20	33	63				116	48	68	128				243
	Breach + 3 Years	0.06	3	21	35	63			122	6	65	82	121			274
	Breach +12 Years	0.07	7	22	35	69			134	20	43	75	147			284
Hazlewood Marshes	Natural	0.05	4	8	20	38			70	11	25	63	127			226
	Pre-breach	0.03	15	31	43	105	199		393	9	18	31	85	135		278
	Breach +2 Years	0.03	3	33	62	96	200		394	3	22	38	69	130		262
	Breach + 3 Years	0.04	3	40	52	98	198		391	1	29	38	63	138		269
	Breach +4 Years	0.04	7	40	42	110	202		401	6	24	29	79	138		276
	Breach +7 Years	0.04	2	39	54	97	195		387	1	30	41	68	139		279
Cattawade	Natural	0.09														
	9	23	36	96	192		356	17	47	79	174	391		707		
	Pre-breach	0.06	2	75	69	65	217		428	2	62	77	242	683		1065
	Breach +1 Year	0.06	5	41	66	82	205		399	4	39	100	229	528		900
	Breach + 2 Years	0.05	2	5	52	42	72	179	352	3	9	82	103	156	407	760
Horsey Island	Natural	0.08	30	35	82				147	45	59	134				237
	Pre-breach	0.05	10	42	56	112	224		444	4	22	35	71	132		264
	Breach +2 Years	0.04	34	39	61	100	236		470	12	22	38	54	134		260
	Breach + 3 Years	0.04	30	49	33	117	232		461	13	32	20	69	130		264
Southmoor	Natural	0.03	6	23	50				79	6	32	54				92
	Pre-breach	0.04	2	5	8				15	5	34	63				102
	Breach +1 Year	0.04	1	7	10				18	8	43	50				101

channels forming the drainage system in uMR sites are former agricultural ditches and drainage features. As a result of former agricultural drainage features becoming part of the drainage network in uMR sites, these sites may not be delivering the full range of ecosystem services seen in natural saltmarshes. One solution could be to infill existing drainage networks, and reinstate former creek networks, as implemented during site construction at Hesketh Out Marsh, Ribble Estuary, northwest England (Tovey et al., 2009). Observations made from satellite and aerial imagery of reclaimed former intertidal areas suggest that the remnant signature of these features can still be detected, however the benefits of restoring these features (if any) both MR and uMR sites remains unknown. Furthermore, although creeks play an important role in encouraging horizontal flows and aerating the soil (e.g. Xin et al., 2013), resulting in a higher plant species richness (Sanderson et al., 2000), the influence of different creek network designs in restored sites requires further investigation. Moreover, research into the impact of creek design on the level of coastal flood defence (Stark et al., 2016) and the use of these features by crustaceans and fish species (Burgess et al., 2020; Callaway, 2005) is required.

In addition to further assessments into site morphology, there is a need for further research into potential ecological benefits of uMR and the delivery of ecosystem services by these sites. Whilst studies of restored sites are limited temporally, the UK's oldest MR sites (Northey Island, Blackwater Estuary) breaching in 1991 (Wolters et al., 2005), studies of uMR could also be conducted at historically de-embanked sites which breached naturally during storm events (Cundy et al., 2002; Spencer et al., 2017). Analysis of these sites will provide a longer-term, in some cases >100 years, insight to the evolution and development of uMR sites. From this, the parameters driving success can then be determined to identify areas appropriate for uMR and to inform the design of future MR sites. These assessments can also inform management and policy decisions, with uMR fulfilling an important role in shoreline management planning.

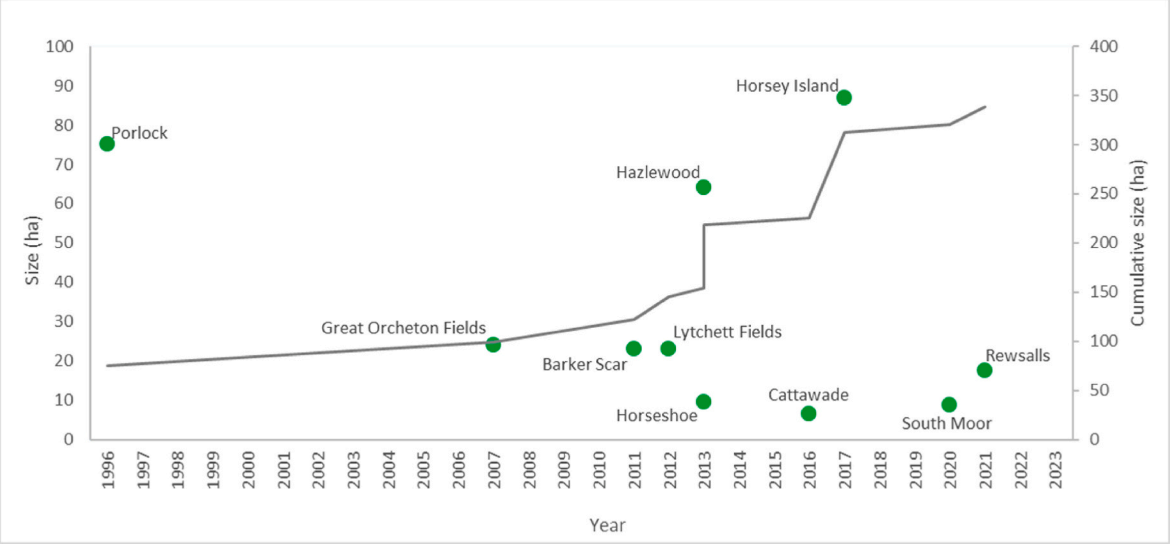

Fig. 3. Occurrence (x-axis), size (left y-axis, points), and cumulative size (right y -axis, solid line) of unmanaged realignment sites in England described in this study.

4.2. Integrating uMR in shoreline management planning

In England, shoreline management decisions are made through Shoreline Management Plans (SMPs). SMPs divide the coastline into cells (Motyka and Brampton, 1993), based on the direction of sediment movement, topography, and morphology to consider the implications of management and defence schemes for the entire coastal system. Within these cells, the coastline is divided further into policy units, where decisions are made by relevant authorities and stakeholders to either Hold the Line, Advance the Line, Manage Realignment, or No Active Intervention (essentially allowing uMR to take place) across three Epochs (or time horizons). Of the ten sites identified in this study, only the breaching at Cattawade and Southmoor occurred in locations where the policy was to Hold the Line until 2105 (Table 4); Southmoor had previously been identified as a potential site for MR but plans had not be pursued due to the cost of removing infrastructure from the site.

Despite the long-term strategic planning set out in SMPs, only a comparatively small area of the realignment (managed or unmanaged) envisaged in the SMPs has been delivered (Committee on Climate Change, 2018). One reason for the lack of realignment is that No Active Intervention (NAI) is often considered 'walking away', creating a negative public perception of MR polices (Esteves, 2014). This is likely to be even more so with uMR due to the lack of intervention and uncertainty in predictions of where and when a site may breach. Consequently, there is a need for efficient and appropriate communication and community engagement to ensure the success of uMR (Yamashita et al., 2019) as a form of shoreline management. Often, arguments against realignment are related to cost (Ledoux et al., 2005), however uMR provides a number of financial benefits, especially given the substantial costs of annual maintenance to sea walls, embankments and barrier beaches. Financial savings can potentially be made both before (if a strategic decision is taken to no longer maintain defences) and after breaching. In contrast, on open coast sites, barrier beach maintenance to a sufficient standard of protection can be high, with a cost of £300,000 pa quoted for the bulldozing of the barrier at Medmerry prior to MR (Cobbold and Waters, 2003). It should, however, be noted that withdrawal of maintenance alone does not guarantee uMR, although it does make the possibility more likely with time.

Table 4
The intent as set out within SMPs for the uMR sites (NAI = No Active Intervention, HTL = Hold the Line, MR = Managed Realignment). **Hazlewood Marsh is part of the Alde-Ore Estuary Plan and not formally within the SMP.*

Location	SMP	Policy Unit	1st Epoch (2005-25)	Realised Policy	2nd Epoch (2026-55)	3rd Epoch (2056–2105)
Porlock	18	7d17	NAI	NAI	NAI	NAI
Great Orcheton Fields	16	6c19	NAI	NAI	NAI	NAI
Barker Scar	22	11c PU12.1	HTL	NAI	MR	NAI
Lytchett Fields	15	PHB. J.2	NAI	NAI	NAI	MR
Horseshoe Lagoon	4	PDZ1	HTL	NAI	MR/ HTL	MR/HTL
Hazlewood Marshes*	7			NAI		
Cattawade	8	A10a	HTL	NAI	HTL	HTL
Horsey Island	18	7c27	HTL	NAI	MR	HTL
Southmoor	13	5a18	HTL	NAI	HTL	HTL
Rewsalls Farm	8	PDZ E2	HTL	NAI	MR	MR

Besides the reduced cost of maintaining flood defences, realignment can lead to increased levels of protection through the attenuation of wave energy, reduced high water levels and flood water storage (e.g. Cox et al., 2006; Kiesel et al., 2022). Due to the projected sea level rise for the UK (Palmer et al., 2018) the prospect of holding the line is also increasingly costly. This situation is set to become more critical with time as a decreasing standard of protection is a function of sea level rise (Sayers et al., 2015). In contrast, the uMR sites presented here are likely to have substantially lower financial capital cost implications when compared to MR due to the lack of engineering works performed during site construction. However, the loss of agricultural land due to uMR may have negative financial implications for those affected due to reduced opportunity for agricultural production (Davis et al., 2019). Nonetheless, given that rising sea levels and the predicted increase in storm magnitude and frequency will increase the risk of overtopping water and flooding at these sites, productivity may well decrease even if flood defences are maintained.

Whilst uMR presents a solution with lower capital cost implications, it is not a financial panacea. Construction and maintenance works may still be required following site breaching. For example, a study identifying potential realignment sites in England, Scotland, and Wales concluded that less than 17% of the total available realignment area was backed by rising ground (Pilcher et al., 2002), with the construction of landward defences required at 80% of potential sites. Moreover, in locations where landward defences are present, work may be required to upgrade or preserve these defences, whilst at all sites public rights of way may need retrospectively rerouting (Pontee et al., 2021) and amendments made to communication and utilities infrastructure; the cost of which contributed to the decision not to conduct MR at the Southmoor uMR site described in this study.

In addition to the financial considerations, the wider implications of uMR also need to be considered. Coastal and estuarine reclamation has been an ongoing global process for several centuries, with the process of realignment restoring some, but not all, of the previously lost accommodation space of systems (Morris and Mitchell, 2013). In doing so, it is likely that uMR will increase the tidal prism of estuarine sites resulting in the re-establishment of natural processes. It is, therefore, important that the implementation of uMR is considered alongside implications for the whole estuarine system. For example, Dale et al. (2021) reported the widening of the main channel leading into Cwm Ivy Marsh, resulting in the erosion and loss of natural saltmarsh, due to the changes in hydrological regime following uMR. Similar observations were also made by Symonds and Collins (2007) at Freiston Shore MR site, The Wash, following breaching. Practical decisions will have to be made to reconcile the loss of natural marsh at the expense of marsh recovery. Furthermore, it is important that, due to the possibility of more water being drawn into the estuary, water levels and upstream flood risk are not increased (Burgess et al., 2014). It had been suggested that breaching at Horsey Island, described herein, may have resulted in almost a 3% increase in the volume of the estuary (Pethick, 2007). Whilst further study is required to validate these predictions, it highlights the importance of considering the influence of uMR at a system level, in order to ensure that restoration efforts, delivered through engineering or through taking a strategic shoreline management decision, benefit overall ecosystem service delivery.

5. Conclusion

This paper provides new insights into the development of recent uMR sites in England, describing ten sites which have breached since 1996. These sites have occurred in locations where existing flood defences have breached naturally by tidal waters following storm events or sluice failure. Analysis of the morphological evolution of five sites indicates that, generally, they have a higher density of creeks prior to site breaching in comparison to natural sites, but lack topographic variability and complex creek morphology. As such, it is likely that these sites are not yet delivering the full range of ecosystem services found in established marshes, although further research is required to assess the influence of morphology on vegetation colonisation in these environments. Despite this, uMR should continue to be considered as a shoreline management option as sites will provide ecosystem services such as more sustainable coastal flood defence, carbon storage, water quality regulation, habitats for juvenile fish species, along with a potential reduction in capital costs for coastal defence maintenance. The wider impact of uMR on whole systems requires further consideration to ensure uMR sites have a positive impact on the strategic delivery of shoreline management planning.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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