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Characteristics of realigned dikes in coastal Europe: Overview and opportunities for nature-based flood protection

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ABSTRACT

Managed realignment is the landward relocation of flood infrastructure to re-establish tidal exchange on formerly reclaimed land. Managed realignment can be seen as a nature-based flood defence system that combines flood protection by the realigned dike (artificial) and restored saltmarshes (nature-based). So far, research on coastal managed realignment is primarily directed to saltmarsh restoration on formerly reclaimed land. This study focuses on the realigned dikes. The aim of this research is to characterize realigned dikes and to indicate the characteristics that offer opportunities for nature-based flood protection. We categorized 90 European coastal managed realignment projects into two realigned dike groups: (1) Newly built landward dikes and (2) Existing landward dikes of former multiple dike systems. The second group has two subcategories: (2a) Former hinterland dikes and (2b) Realignments within summer polders. For each group we present the realigned dike characteristics of a representative case study. We consider that the use of existing landward dikes or local construction material make realignment more sustainable. From a nature-based flood protection perspective, the presence of an artificial dike is ambiguous. Our results show that targeted and expected saltmarsh restoration at managed realignment does not necessarily result in a greener realigned dike design that suits for combined flood protection with restored saltmarshes. We recommend coastal managers to explicitly take combined flood protection into account in the realigned dike design and steer the topography of the realignment site to facilitate nature-based flood protection and promote surface elevation increase seaward of the realigned dike in response to sea level rise. This makes managed realignment a nature-based flood defence zone for now and for the future.

1. Introduction

Dikes form an essential part of flood risk management in many low-lying coastal regions. They have protected inhabitants from high water levels and wave impact for centuries. In addition, dike construction enabled polderisation and enlarged agricultural land surface as the dikes protect low-lying agricultural land from regular tidal inundation and flooding (e.g., Van der Ham, 2009). However, dikes do not only prevent flooding, they also inhibit sediment transport to low lying hinterlands and subsequently increase the elevation difference between this land and the water (Syvitski et al., 2009; Temmerman et al., 2013). Dikes hereby form a barrier that hampers sustainable coastal development, especially regarding intertidal habitat conservation and development (e.g., Pontee, 2013). Presently, coastal managers face the need for coastal dike adaptation to anticipate for the foreseen sea level rise induced by climate change (e.g., Nicholls et al., 2018; Oppenheimer et al., 2019). In the coming decades, efficient, adaptable, and environmentally sustainable dike reinforcement methods are required to ensure safety from coastal flooding and to reduce flood damage costs (Hinkel et al., 2014; Vousdoukas et al., 2020). European policy now prioritizes nature-based solutions for adaptations (the EU Green Deal; European Commission, 2021). Therefore, there is growing interest to make dikes greener for instance by applying a vegetated revetment or combining grey and green infrastructure (e.g., Schoonees et al., 2019). Recently, managed realignment (MR) was recognized as a promising climate change adaptation measure that adds to traditional dike management and reinforcement strategies and allows for sedimentation on low-lying coastal land to reduce the impact of future sea level rise (Esteves, 2014a; Temmerman et al., 2013; Zhu et al., 2020).

MR is the landward relocation of flood infrastructure to re-establish tidal exchange on formerly reclaimed land (Fig. 1) (Bridges et al., 2021; French, 2006). The goals of MR include nature restoration, flood

Abbreviations: MR, managed realignment.

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protection, and providing other ecosystem services like recreation (e.g., Esteves, 2014a). Prior to realignment, the old seaward dike is usually modified and its primary flood defence function is shifted towards the landward dike. Possible modifications of the old seaward dike are lowering, breaching, or removing (Fig. 1) or implying regulated tidal exchange via gates, pipes, or sluices (Esteves, 2014c). These modifications enable regular inundation and delivery of sediment to the low-lying land between the old seaward dike and the landward relocated dike (e.g., Liu et al., 2021). We define the landward relocated dike as the realigned dike. The realigned dike is, likewise all dikes, an artificial element that ensures sufficient flood protection of the hinterland (CIRIA, 2013). As mentioned by the International Levee Handbook (CIRIA, 2013) the dike design for flood protection includes geotechnical parameters such as dike slope, revetment, and crest height. Realigned dikes are either newly built (type 1) or were already existing as part of multiple dike systems (type 2 in Fig. 1). The existing landward dike is sometimes reinforced to meet the required safety standards. MR can be realized and described in many variations (Esteves, 2014b), including: de-poldering (e.g., Goeldner-Gianella, 2007a; Van Staveren et al., 2017), realignment towards a natural high topography (e.g., Wheeler et al., 2008), controlled tidal restoration (e.g., Oosterlee et al., 2019), flood control areas (e.g., Cox et al., 2006), managed retreat (e.g., Abel et al., 2011), and physical realignment of defences (Esteves, 2014c). The focus of this paper is on realignment of defences.

Landward realignment of a coastal dike fosters the restoration of natural foreshores (e.g., Liu et al., 2021; Schuerch et al., 2018). A coastal foreshore is the intertidal habitat fronting a dike, such as mudflats and saltmarshes (e.g., Vuik et al., 2016). Vegetated saltmarshes, in particular, provide many ecosystem services (Barbier et al., 2011), including flood risk reduction by wave, high water level, and storm surge attenuation, shoreline stabilization, and wave impact reduction on the adjacent dike (e.g., Gedan et al., 2011; Shepard et al., 2011; Stark et al., 2015; Van Loon-Steensma and Kok, 2016). Wave energy is dissipated by a combination of foreshore elevation and width, and vegetation presence (e.g., Battjes and Groenendijk, 2000; Möller et al., 2014, 2001; Vuik et al., 2019; Willemsen et al., 2020). Zhu et al. (2020) showed that the presence of wide saltmarshes in front of a dike reduces the risk and impact of breaching. Furthermore, saltmarshes can grow with sea level rise through sedimentation (Allen, 2000; Kirwan et al., 2016) and the presence of saltmarshes thus could reduce flood costs (Fairchild et al., 2021). These properties make saltmarshes promising for environmentally and economically sustainable flood protection.

MR offers an interesting opportunity for coastal managers to integrate saltmarshes in flood protection (e.g., Bouma et al., 2014). In MR, restored saltmarshes can be combined with the realigned dike to form one nature-based flood defence zone. A nature-based flood defence includes a natural system to reduce flood risk and simultaneously provide other ecosystem services (e.g., Van Wesenbeeck et al., 2014). Within MR flood protection is provided by an artificial part, the realigned dike (e.g., CIRIA, 2013) plus old primary dike remnants that can act as wave breakers (Hofstede, 2019), and a nature-based part, the restored saltmarshes (e.g., Vuik et al., 2019). Combining the two parts includes a transition between the saltmarshes and dike. An uninterrupted physical connection, where the saltmarsh reaches the realigned dike, will facilitate this transition and make MR more suitable for combined flood protection. For example, a saltmarsh that merges into a wide green dike (Van Loon-Steensma and Schelfhout, 2017). Interruption, for instance by a concrete path, rock armour, a ditch, or a fence, can limit this transition.

While the realigned dike is static, the restored saltmarshes can reduce future flood risk under sea level rise by facilitating sedimentation on former low-lying land (e.g., Liu et al., 2021). The low-lying land was originally protected from inundation by the seaward dike. The dike also blocked sediment transport to this land, thereby limiting accretion and consequently, surface elevation increase. Dike realignment re-opens the low-lying land to tidal flow and sediment input. Subsequently, saltmarshes can restore and increase elevation in front of the realigned dike. The raised land aids in flood protection (e.g., Battjes and Groenendijk, 2000; Le Hir et al., 2000) and might eventually serve as temporary farmland again (Zhu et al., 2020). The associated land use switch is described by the concept 'transitional polder': a former polder is reopened to tidal flow, intertidal habitat builds up with sea level rise, and the raised land turns into agricultural land again (e.g., De Mesel et al., 2013; Zhu et al., 2020). This concept is, on a different scale, similar to the old earthen embankments in Bangladesh. During dry months they protected agricultural land from saline water but during monsoon months they washed away and allowed sedimentation (Dewan et al., 2015).

While MR can be seen as a nature-based flood defence zone, the presence of the realigned dike is ambiguous from a nature perspective. On the one hand the realigned dike ensures sufficient flood protection of the hinterland which allows geomorphological processes to restore saltmarshes on the formerly reclaimed land. These saltmarshes can then provide nature-based flood protection. On the other hand, a dike reduces landward accommodation space and thereby limits saltmarsh restoration (Pontee, 2013). Until now MR research is primarily directed to saltmarsh restoration on the formerly reclaimed land (e.g., Chang et al., 2016; Liu et al., 2021; Morris, 2013; Reed et al., 2018; Wolters et al., 2005). Other characteristics of MR, such as breach design and realignment area size, have been described (e.g., Townend, 2008 and Kiesel et al., 2020 respectively), but so far, the realigned dike received less attention in scientific literature. Therefore, the focus of this study is on realigned dikes. The aim of this research is to characterize realigned dikes and to indicate the characteristics that offer opportunities for nature-based flood protection. Our study contributes to making realigned dikes greener and more suitable for combined flood protection with restored saltmarshes. Scientific articles and research reports were reviewed to make an overview of realigned dikes in coastal Europe. The realignment projects were grouped based on the different types of realigned dikes (i.e., whether the dike was newly built as part of the realignment scheme or already existing as part of a former multiple dike

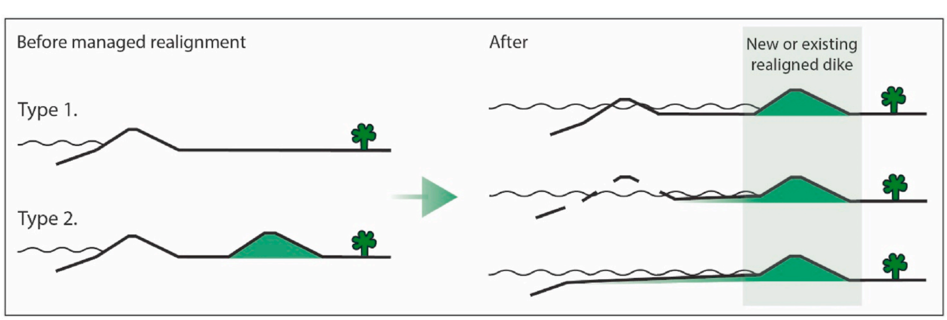

Fig. 1. Managed realignment, the general concept shown by cross sections of the dikes. The left side represents the initial situation with either only a primary dike (type 1) or a multiple dike system (type 2). The right side shows the situation after dike realignment with optional modifications to the old seaward dike (lower, breach or remove).

system). Subsequently, realigned dike characteristics were compared for representative case studies. Finally, the realigned dikes were discussed from the perspective of nature-based flood protection. While the presence of an artificial dike makes MR less natural, we discuss dike and MR site characteristics that offer opportunities for nature-based flood protection. This discussion can inform coastal managers for future MR projects.

2. Methodology

2.1. Selection of managed realignment projects

We started our analysis with selecting European MR projects (step 1 in Fig. 2). We collected information from scientific articles, accessible Dutch and English research reports and open access databases. An initial list was composed using the Online Managed Realignment Guide (OMReG) and the overview provided by Esteves (2014). This list was updated by consulting literature and searching Google. Scientific literature was searched in the database Scopus. Main search term was: “managed realignment” in all fields, which resulted in 1094 hits. Additional search terms were: “managed realignment” AND “dike” (73 hits), “managed realignment” AND “dyke” (38 hits), and “managed realignment” AND “flood defence” OR “flood defense” (179 hits). The general term ‘flood defence’ enabled identification of articles with varying flood defence terminology such as embankment or seawall. Only Dutch and English documents were included in the initial search. For each search combination, titles and abstracts were scanned to complete the list of realignment projects and to indicate relevant journal papers, reports and book chapters. Additional and ongoing realignment projects were searched for using Google search engine. This additional search provided information from general public websites of e.g. NGOs and regional authorities on nature reserves and realignment projects.

Next, the MR list was curtailed to focus on open coasts and protected inlets where potential sedimentation stimulated by realignment can reduce the impact of future sea level rise (step 2 in Fig. 2). The selection included coastal, estuarine, lagoon, fjord, and bay locations that have tidal influence, wave or surge attenuation capacity, and saline to brackish water. Fluvial sites and freshwater tidal wetland projects such as undertaken in the Dutch Room for the River program were thus excluded. The next step was selecting MR projects with a landward realigned dike (step 3 in Fig. 2). Selection was based on information from literature and satellite images in Google Earth. The latter gave an impression of dike locations before and after realignment. The final MR overview only included projects with a ‘realignment of defences’ (Esteves, 2014c) where natural tidal exchange is facilitated through breaching, removal or lowering of the original dike (Fig. 1). Therefore, the following types of projects were excluded from our analysis: controlled tidal restoration, regulated tidal exchange, managed retreat (relocation of people and property, e.g., Abel et al., 2011) and where flood risk was controlled by a natural rise in topography (no new or existing dikes). We note that the definitions used in this paper serve the purpose of our research focus on realigned dikes but might differ from the variety of definitions found in the wider MR literature (e.g., Esteves, 2014b).

2.2. Data analysis

The overview of European MR projects was used to distil the characteristics of the realigned dikes. For each realignment project we provided information on location, coastal setting, year of initiation, main reason for realignment, the size of the realignment site in hectares, and the realigned dike. The realigned dike could be newly built or was already existing as part of a former multiple dike system (Fig. 1). We include two types of multiple dike systems: a primary dike with another dike landward (hinterland dike, situated within a polder) or a primary dike with another dike seaward (foreland dike, such as a summer dike) (Van Loon-Steensma et al., 2014). We use the type of realigned dike to study greener dike design (i.e., a dike design that includes adjacent foreshores (e.g., Schoonees et al., 2019)). When a new landward dike is built to allow for realignment, one expects saltmarsh restoration in front of this new dike. In this review we looked if the targeted and expected saltmarsh restoration resulted in an adapted, greener, realigned dike design that facilitates combined flood protection by the dike and saltmarshes. So, the realigned dikes were grouped based on whether the dike was newly built or already existed (step 4 in Fig. 2).

For each realigned dike group, we selected one representative case study to delve into the realigned dike characteristics that offer opportunities for nature-based flood protection. First, we looked into more detail at the location of each case study. Local wave climate and tidal regime were studied using literature and open access databases. Foreshore presence and approximate foreshore area were briefly studied by using literature and Google Earth. Second, we focussed on the realigned dike in each case study. We described realigned dike characteristics such as dike length, dike profile, dike steepness, dike height, construction

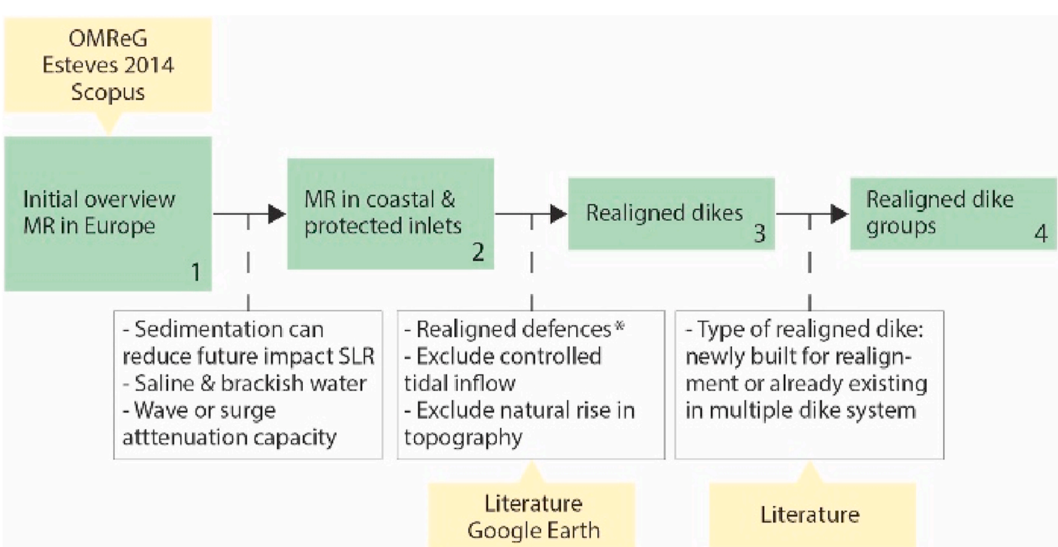

Fig. 2. Overview of managed realignment (MR) project selection to form realigned dike groups. Including data input (yellow boxes) and selection criteria (white boxes). *Esteves (2014c).

material origin, and dike revetment. Finally, we discussed the case studies from the perspective of nature-based flood protection by studying dike design (dike steepness and dike revetment) and site elevation in relation to the tide at realignment initiation. We also discussed the environmental sustainability of realigned dikes by analysing two aspects: construction material origin and whether the realigned dike was newly built, already existed, or reinforced. We consider the use of local construction material more sustainable than importing construction material or manufacturing construction material due to amongst others lower CO_2 emissions and reduced transportation.

3. Results

3.1. European coastal managed realignments grouped by the characteristics of the realigned dike

Our analysis resulted in an overview of 90 coastal European MR projects (Fig. 3 and Table A1 in the Appendix). Hereby we added 15 realignment projects to the existing MR overview by OMReG (Esteves, 2014 and OMReG website). At the moment of writing, at least 89 coastal realignments have been completed in Belgium, Denmark, England, France, Germany, Scotland, Spain, and the Netherlands (Fig. 3) and at least one realignment is under construction: the Hedwige-Prosperpolder realignment (#51, Van den Hoven et al., 2021). The majority of European realignments is in England, Germany, and the Netherlands (Fig. 3 and Table 1). Average size of the 90 realignments is 155.4 ha, median size 37.5 ha, minimum size 0.8 ha, and maximum size is 3,600 ha (Table A1). About one third of the 90 projects is located at the exposed coast and about two thirds are located in protected inlets, most of them in estuaries and several in fjords, lagoons, and bays (Fig. 3 and Table 1). For example, the Humber estuary hosts many realignments as part of the Humber Estuary Shoreline Management plan (Winn et al., 2003). These include: Chowder Ness (#08), Paull Holme Strays (#25), and Welwick (#34) (Table A1).

To see if the targeted and expected saltmarsh restoration resulted in an adapted realigned dike design we distinguish two main realigned dike groups: (1) Newly built landward dikes (36 MRs) and (2) Existing landward dikes of former multiple dike systems (54 MRs). The second group has two subcategories: (2a) Former hinterland dikes (39 MRs) and (2b) Realignments within summer polders (15 MRs) (Table 1). The realigned dikes in group one were newly built to protect the hinterland from flooding after the realignment. The realigned dike in subcategory 2a already existed as the hinterland dike of a primary flood defence within a multiple dike system. This includes historical dikes that were not subjected to flooding anymore. After realignment, the hinterland dike became the primary flood defence. If necessary, the existing

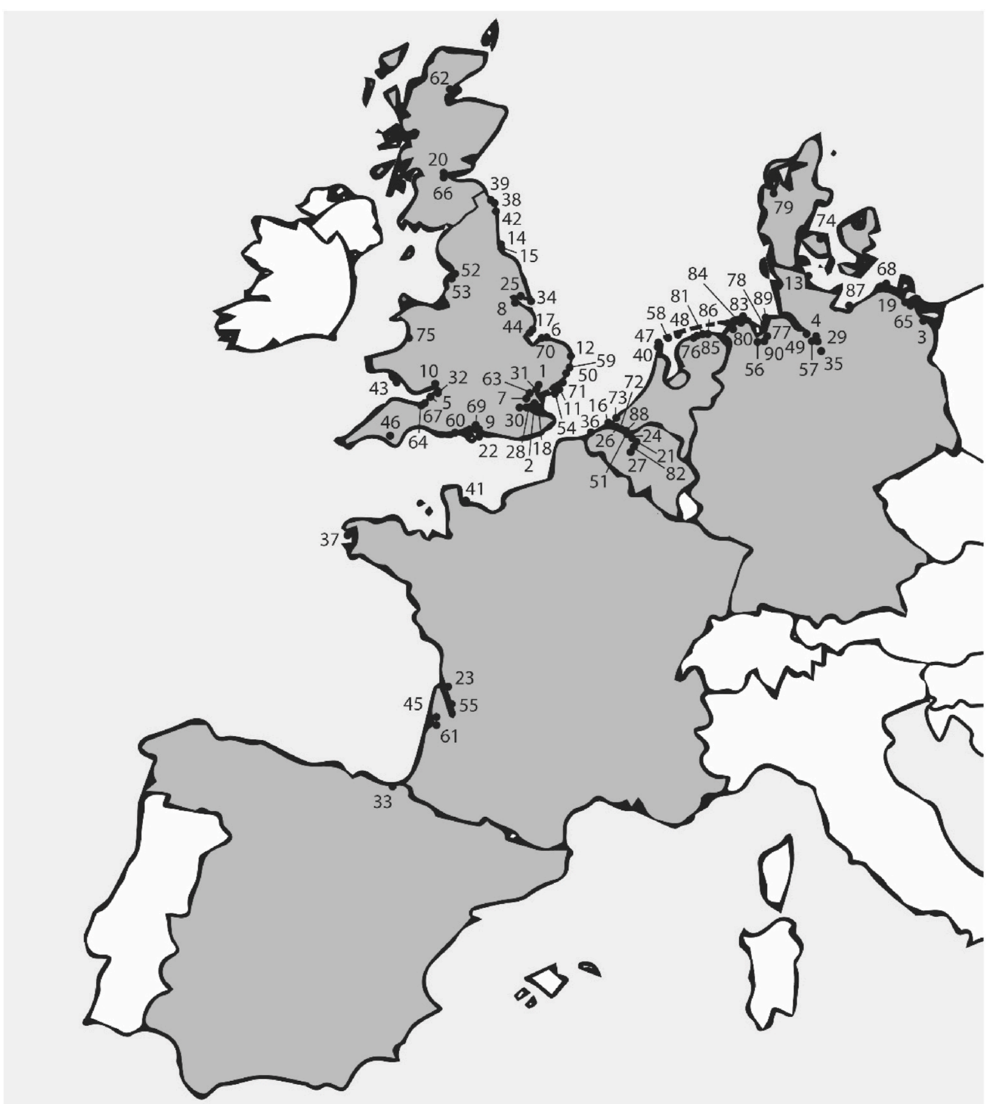

Fig. 3. Locations of the 90 coastal European managed realignment projects in our overview. Numbers correspond with Table A1 in the Appendix.

Table 1
Number of managed realignment projects in each realigned dike group, per country and coastal setting (based on Table A1 in Appendix). 0.5 numbers due to two projects on the border of two countries.

Realigned dike	Coast	Total	Open	Estuary	Bay	Lagoon	Fjord
	Country	90	28	53	4	3	2
1 Newly built		36	7	27	0	2	0
	Belgium	4.5	0.5	4			
	Denmark	0					
	England	21	4	16		1	
	France	1		1			
	Germany	6	2	3		1	
	Netherlands	1.5	0.5	1			
	Scotland	1		1			
	Spain	1		1			
2a Former hinterland		39	11	23	3	1	1
	Belgium	0.5		0.5			
	Denmark	1					1
	England	19	2	16		1	
	France	5	2	1	2		
	Germany	5	1	3	1		
	Netherlands	6.5	5	1.5			
	Scotland	2	1	1			
	Spain	0					
2b Summer polder		15	10	3	1	0	1
	Belgium	1		1			
	Denmark	1					1
	England	0					
	France	0					
	Germany	8	6	1	1		
	Netherlands	5	4	1			
	Scotland	0					
	Spain	0					

landward dike was reinforced to meet safety standards. In subcategory 2b the realigned dike was part of a multiple dike system where a primary dike had a seaward summer dike. In the descriptions of these MRs was an explicit mentioning of either summer dike or summer polder before realignment, subcategory 2b locations had a lower summer dike fronting the sea or estuary and a higher landward winter dike. In summer, the area between the two dikes remained relatively dry so it could be used for agriculture or grazing. In winter, this area was incidentally subjected to flooding. After realignment, the former summer polder is subjected to flooding with every tide.

The reason for realignment initiation differed between locations and between the realigned dike groups. First of all, realignment initiation was deliberate at 77 locations, and for the other 13 locations there were accidental breaches reported (Table A1). While accidental breaches are not always considered managed realignment (Esteves, 2014b), they are included in this study as long as there is a choice of either landward realignment or breach repair. For instance, the Sieperda marsh in the Netherlands (#88 Fig. 3), where an accidental summer dike breach during a storm in 1990 lead to the managed development of the former Selena polder into the Sieperda tidal marsh (Eertman et al., 2002). Most accidental breaches were found in (2a) Former hinterland dikes (9 out of 13). In contrast, each of the other realigned dike groups had only two MR projects with accidental breaches (Table A1). To illustrate, five out of six French realignments originate from accidental breaches and five out of the six belong to (2a) Former hinterland dikes (Table A1). At least in Arcachon Bay, where Graveyron Polder (#45) and Malprat island (#61) are located (Fig. 3), MR is cheaper than the repairment of accidental breaches if existing hinterland dikes are used for flood protection (Goeldner-Gianella et al., 2015). This shows that if an accidental breach occurs in the seaward dike of a former multiple dike system, breach repairments are not always necessary. Especially when breach repairments are too costly or impossible due to environmental legislation, MR can be a solution to provide sufficient flood protection after an accidental breach in the seaward dike of a multiple dike system.

Nature restoration is a driver in the majority of realignment projects (32 out of 36 New landward dikes, 27 out of 39 Former hinterland dikes, and 13 out of 15 Realignments in summer polders, Table A1). However, the groups differ when also looking at realignment initiation for flood protection. Flood protection was a driver for realignment initiation at 17 out of 36 New landward dikes and at 15 out of 39 Former hinterland dikes (Table A1). In contrast, only two summer polder realignments aimed at both nature restoration and flood protection (#85 Noarderleech and #82 Ketenisseschor, Table A1) and most Realignments in summer polders have been driven only by nature restoration (11 out of 15, Table A1). The focus on nature restoration in former summer polders might be explained by the presence of the winter dike. The existing flood protection function of the winter dike reduces the need for improved flood protection through MR while simultaneously it allows for saltmarsh restoration seaward of the winter dike. However, MRs mainly driven by nature restoration can still co-benefit flood protection. For example, the summer dike realignment at Cappel-Süder-Neufeld (#77 Fig. 3) aimed specifically at nature conservation but afterwards Saathoff and Lange (2012) also reported positive impacts on flood protection related ecosystem services.

3.2. Realigned dike groups illustrated with case studies

The realigned dike groups are each illustrated and explained with a representative case study (Fig. 4). The three case studies are: 1 Newly built landward dike at Lillo Potpolder (Belgium), 2a Former hinterland dike at Hedwige-Prosperpolder (on the border of Belgium and The Netherlands), 2b Realignment within summer polder at Noarderleech (The Netherlands). For each case study, we describe the MR project and the realigned dike characteristics.

3.2.1. Newly built dike at Lillo Potpolder

The first case study is the Lillo de-polderisation along the Scheldt Estuary in Belgium (#21, Fig. 4). Realignment of the polder was part of the ongoing Belgium Sigmaplan that aims at tidal nature restoration and flood protection while it also takes recreation and economic value into account (e.g., De Beukelaer-Dossche & Van den Bergh, 2013). Main reasons for realignment at the Lillo Potpolder were intertidal habitat

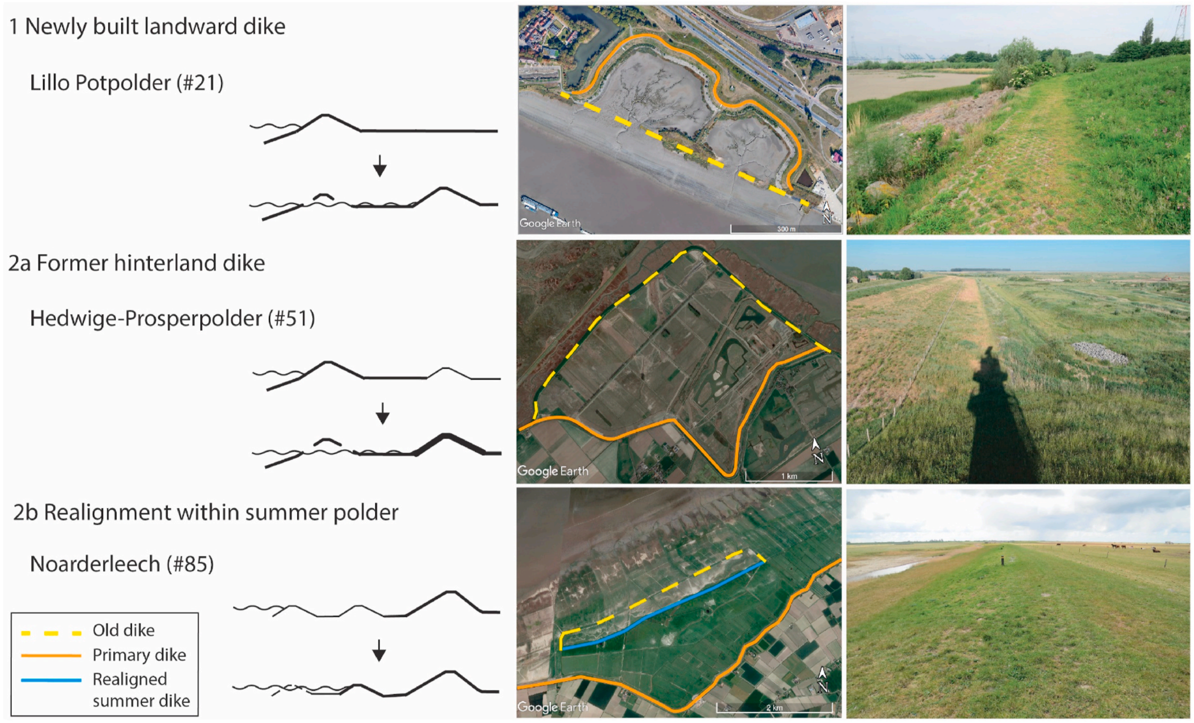

Fig. 4. The realigned dike groups with representing case studies showing the realigned dike (right column). Dike modifications in the cartoons are similar to Fig. 1. Case study numbers correspond with Fig. 3 and Table A1 in the Appendix. Google Earth image dates: 1 20-09-2019; 2a 11-04-2020; 2b 01-06-2017. Photographs by K. van den Hoven (1 & 2b) and A.J. van den Hoven (2a).

restoration and to form a pilot study for the influence of breach design (www.sigmaplan.be and *pers. com.*). Tidal range in this brackish part of the Scheldt estuary is 5.2 m (Waterbouwkundig Laboratorium getijtafels Beneden-Zeeschelde), with average spring tides of 3.4 m above mean sea level (in 2020, Vandenbruwaene et al., 2021). Waves mainly originate from ships as the Lillo Potpolder is located in the port of Antwerp. Prior to realignment, the Lillo Potpolder was a deposit for sediment remnants from the Liefkenshoek tunnel construction (one of the main tunnels through the Scheldt Estuary; Degroof, 1992). In 2012, the 10 ha Lillo Potpolder was realigned in two compartments. Part of the original dike was lowered to high water level (160 m wide) and a part was removed to create a 170 m wide breach. Elevation of the area between the old and new dike remained between 1.67 and 2.17 m above mean sea level. The foreshores fronting the de-polderised Lillo Potpolder have developed in the past years. Back in 2008, the foreshores consisted of only a 10–20 m wide saltmarsh and approximately 100 m of tidal flats (Piesschaert et al., 2008). Since 2008, sedimentation occurred near the dikes but erosion was observed near the channels (Van Braeckel et al., 2019; Van Ryckegem et al., 2014; 2013). Subsequently, the Lillo Potpolder realignment led to saltmarsh expansion (Van Braeckel et al., 2019; Van Ryckegem et al., 2014; 2013).

The realigned dike at Lillo Potpolder is a newly build ring dike of 1.1 km. The dike height meets the Sigma norms, it is 8.67 m above mean sea level (R. Vanhooydonck, *pers. com.*). The dike has a 1.5 m clay top layer with a rubble dike toe protection. Part of the rubbles are additionally covered with asphalt (R. Vanhooydonck, *pers. com.*). Most of the dike, including the rubbles, is covered by vegetation that includes grasses, herbs, and shrubs (personal observation in summer 2021). There is an asphalt maintenance/bicycle path on the dike crest. Part of the dike has a path on the outer berm that consists of a combination of concrete grass paver blocks (10 cm), geotextile, sand and gravel (3 cm), and a crushed stone foundation (32 cm) (R. Vanhooydonck, *pers. com.*). Most dike construction material was locally resourced. The Lillo Potpolder itself provided sediment and the old dike along the Scheldt served as a resource for the new dike.

The transitional polder concept (De Mesel et al., 2013; Zhu et al., 2020) is demonstrated by the different land uses of the Lillo Potpolder (W. Mertens, *pers. com.*). The Lillo Potpolder used to be part of the Scheldt Estuary. After the construction of dikes, water was kept out and the Lillo and Pot polders were created. In 1831, during Dutch occupation, a dike breach resulted in flooding of the polders (www.scheldeschorren.be). In 1838, a new dike was built to keep water out of part of the polder area (www.scheldeschorren.be). Only in 1906, the Pot polder was polderised again and the entire Lillo Potpolder was protected from flooding by dikes (www.scheldeschorren.be). For decades, the polder has been used as a sand stock (Degroof, 1992) and polder elevation was relatively high. To enable realignment in 2012, sand in the polder was excavated and recycled in dike construction. The de-polderisation decreased the elevation in the Lillo Potpolder area. However, the return of tidal flow led to elevation increase again (Van Braeckel et al., 2019; Van Ryckegem et al., 2014; 2013).

3.2.2. Former hinterland dike at Hedwige-Prosperpolder

The second case study is the ongoing Hedwige-Prosperpolder de-polderisation along the Scheldt estuary (e.g., Van den Hoven et al., 2021) (#51, Fig. 4). The realignment area includes the Dutch Hertogin Hedwige polder (average elevation of 2.00 m above mean sea level) and the Northern part of the Belgium Hertog Prosper polder (average elevation of 1.50 m above mean sea level) (Van den Bergh and Mertens, 2005b). Main reason to realign 465 ha of former agricultural land is tidal nature restoration as compensation for extension of the port of Antwerp. At the Dutch-Belgium border, the Scheldt estuary is brackish, the tide is semi-diurnal and average tidal range is 5.00 m (Mobility and Public Works department of Flanders government, available at www.waterinfo.be), with high water levels of 2.19–3.24 m above mean sea level for neap and spring tide (www.waterinfo.be). Wave climate is mild and waves are generally produced by ships navigating to Antwerp's port. At the moment of writing, the realigned dike has been finalized while other preparations for the realignment are still ongoing to facilitate tidal flow and to stimulate saltmarsh restoration inside the former polders (Van den Hoven et al., 2021). The old primary dikes along the Scheldt estuary will be lowered and breached. Reed foreshores that fronted the old primary dikes were elevated over 3.0 m above mean sea level. They are being lowered by mowing the reed, removing sediment, and excavating creeks. In addition, elevation of the two polders is being levelled and creeks have been excavated inside the polders.

The realigned dike at the Hedwige-Prosperpolder is mainly constructed along existing landward dikes (Fig. 4). These existing dikes required reinforcements to get a crest height between 9.70 and 10.20 m above mean sea level (Soresma, 2013). In addition, one part of the realigned dike was newly built to separate the Prosperpolder into North and South. The outer slope of the realigned dike is 1:6 (bottom) and 1:4 (top) while the inner slope is 1:3 (Soresma, 2013). The dike has a sand body with a clay revetment that is covered with open stone asphalt to allow vegetation growth, mainly grass. The dike toe is reinforced with armour rock and geotextile (Soresma, 2013). Construction material mainly originates from inside the polders and nearby excavation works around the Scheldt estuary (*pers. com.* and Soresma, 2013). The 4.8 km realigned dike now runs from the Scheldt estuary in Belgium around the former polder area and it connects to the realigned dikes of the Sieperda marsh (#88) and the Verdronken land van Saeftinghe (#72) in the Netherlands (Fig. 4). As preparations for realignment are still ongoing at the moment of writing, saltmarsh development in the new intertidal area fronting the realigned dike has not yet started. Currently, the area is characterized by former agricultural land with excavated creeks (personal observation in autumn 2021).

3.2.3. *Realignment within a summer polder at Noarderleech*

The third case study is the Noarderleech summer dike realignment along the Wadden Sea in The Netherlands (#85, Fig. 4). Main reason for realignment was stimulation of saltmarsh development and accompanied sedimentation in the former summer polder (Van Duin et al., 2007). At Noarderleech, mean tidal range is 2.1 m, with an average spring tide of 1.1 m above mean sea level (RWS Centrale Informatievoorziening, 2013). Before realignment, the Noarderleech area existed of multiple restored saltmarshes, summer polders, and multiple summer dikes that were all bordered by one winter dike (the delta dike, Fig. 4) (Bakker et al., 2001). In 2001, a seaward summer dike was breached to open up 135 ha of former summer polder (elevation 1.0–1.8 m above mean sea level, Van Loon-Steensma and Schelfhout, 2013) to the Wadden Sea tidal influence (Bakker et al., 2001). Three 20–40 m wide breaches were made and a tidal gate was placed inside one of the breaches to limit inflow width to 2.0 m (Van Duin et al., 2007). In addition, creeks were excavated to guide tidal flow (Bakker et al., 2001).

The realigned dike at Noarderleech is thus a summer dike (Fig. 4). Prior to realignment, this landward summer dike was reinforced with clay from the creek excavation (Esselink et al., 2015; Van Duin et al., 2007). The dike was widened and heightened to 3.10 m above mean sea level, the height of the former seaward summer dike (Van Duin et al., 2007). Because the summer dike realignment influenced the intertidal area fronting the winter dike, including the hydrological conditions, we also studied the winter dike.

The winter dike is part of a 12.5 km long wide green dike that forms the primary flood defence (Bakker et al., 2001; Van Loon-Steensma and Schelfhout, 2013). This dike is designed for a storm surge of 5.50 m above mean sea level and significant wave heights of 1.85 m (Van Loon-Steensma and Schelfhout, 2013). The crest height is between 7.60 and 8.40 m above mean sea level (Van Loon-Steensma and Schelfhout, 2013). It has a sand core covered with clay and a grass revetment (Van Loon-Steensma and Huiskes, 2017; Van Loon-Steensma and Schelfhout, 2013). The outer slope is 1:8 and has a 1.50 m thick clay layer while the inner slope is 1:3 and has a 0.80 m clay layer (Van Loon-Steensma and Schelfhout, 2013). Clay originates from the existing dike and intertidal habitat. A maintenance path at the dike toe is covered with concrete grass paver blocks to prevent damage to the grass revetment (Van Loon-Steensma and Schelfhout, 2013). Large scale wave flume tests confirmed the safety of a wide green dike with the presence of foreshores at Noarderleech (Waterloopkundig Laboratorium, 1984). Since the realignment, saltmarsh development has been observed behind the breached summer dike (e.g., Van Duin et al., 2007). The restored intertidal habitat reduces wave height at the Noarderleech winter dike up to 30% and the saltmarsh vegetation further reduces wave height up to 8% (Van der Reijden, 2019). Based on vegetation presence alone, so neglecting the saltmarsh elevation, dike crest height can be reduced by 6 cm (Van der Reijden, 2019).

3.2.4. *The case studies from a nature-based flood protection perspective*

Finally, we study the case studies from a nature-based perspective with focus on combined flood protection by the realigned dike and saltmarshes. With regards to realigned dike design, combined flood protection is best facilitated at the Noarderleech summer polder realignment. The newly built dike design at Lillo Potpolder least facilitates combined flood protection. A steep slope can hamper the transition from the saltmarshes onto the dike. Furthermore, the dike toe at Lillo Potpolder consists of rubbles and asphalt which allows less vegetation growth than the dike toes at the Hedwige-Prosperpolder and Noarderleech (Fig. 4 and Table 2). At Noarderleech, the saltmarshes are already integrated in the winter dike design: the dike has a broad, shallow profile and a complete grass revetment (Van Loon-Steensma and Schelfhout, 2013; Waterloopkundig Laboratorium, 1984).

Table 2
Realigned dike characteristics for the three case studies.

Realigned dike	1 Newly built	2a Former hinterland	2b Summer polder
Case studies	**Lillo Potpolder**	**Hedwige-Prosperpolder**	**Noarderleech**
Length (m)	1,100	4,800	Part of 12,500
Crest height (m)	8.67	9.70–10.20	7.60–8.40
Seaward slope	1:4	1:4 and 1:6	1:8
Revetment	Clay with vegetation Dike toe: rubble, asphalt Path: concrete grass paver blocks, geotextile, sand, gravel, crushed stone	Clay with grass Open stone asphalt with grass Dike toe: armour rock with geotextile	Clay with grass Dike toe: path with concrete grass paver blocks
Construction material origin	Old dike Polder (deposit) Non-local	Polders Works in Scheldt estuary Non-local	Old dike Foreshores Non-local

At all three case studies, elevation of the former reclaimed land allowed regular inundation after realignment initiation. This fosters the restoration of saltmarshes and subsequently the transition between restored saltmarshes and the realigned dike. The former Lillo Potpolder is regularly inundated with elevation below average spring tide (Vandenbruwaene et al., 2021). The Hedwige-Prosperpolder elevation is below the high water levels. However, extended reed foreshores fronting the old seaward dike were highly elevated so tidal flow onto the former polders needs to be facilitated by foreshore lowering and creek excavation (Van den Hoven et al., 2021). At Noarderleech the restored saltmarshes get entirely flooded with water levels higher than 1.9 m above mean sea level (Van Duin et al., 2007). Indeed, saltmarsh restoration is observed in the former summer polder (e.g., Van Duin et al., 2007). So, site elevation plus human induced topographical changes allow water and sediment to flow onto former reclaimed land and restore saltmarshes fronting the different types of realigned dike at the representative case studies.

4. Discussion

4.1. Realigned dikes from a nature-based flood protection perspective

MR can be seen as a nature-based flood defence zone that combines flood protection by the realigned dike and restored saltmarshes. Even at locations where saltmarshes disappeared in front of dikes MR enables the integration of saltmarshes in flood protection (e.g., Temmerman et al., 2013). It has been shown that at least in estuaries, the incorporation of saltmarshes in MR enhances flood risk reduction (e.g., Bouma et al., 2014; Fairchild et al., 2021; Temmerman et al., 2013). Along open coasts the influence of saltmarshes on flood risk reduction depends on the design of MR schemes, especially on the number and size of breaches and the size of the realigned area (Kiesel et al., 2020). In this study we take a next step by looking at the realigned dike.

From a nature-based flood protection perspective, the presence of a dike is ambiguous. Our study contributes to making realigned dikes greener and more suitable for combined flood protection with restored saltmarshes. An uninterrupted transition hereby not only promotes connectivity in terms of natural habitats, it also combines two flood defence features into one flood defence zone. We found that combined flood protection is facilitated by certain realigned dike characteristics and can be steered by topographical adjustments to the realignment site. Although the design of a newly built realigned dike can be tailored to facilitate combined flood protection with the targeted and expected restored saltmarshes, we surprisingly found that the Newly built landward dike at Lillo Potpolder has the least green dike design from all three case studies. So, the targeted and expected saltmarsh restoration did not result in an adapted realigned dike design. This shows that facilitating combined flood protection by the dike and saltmarshes is not obvious yet in the design of MR schemes. To improve realigned dike design we recommend to apply the shallow dike profile and grass revetment as at Noarderleech, similar to a ‘Wide green dike’ as presented by Van Loon-Steensma and Schelfhout (2017), to newly built or reinforced existing landward realigned dikes.

In addition to a tailored realigned dike, the former reclaimed land can be prepared for saltmarsh restoration. This limits saltmarsh establishment failure (e.g., Mossman et al., 2012). Tidal flow can be guided to increase sedimentation, saltmarsh development, and the accompanied flood protection function. For example, by levelling the elevation or by excavating creeks. These preparations are observed in each realigned dike group, such as at #01 Abbotts Hall and #31 Tollesbury (group 1), #51 Hedwige-Prosperpolder and #53 Hesketh Out Marsh West (subcategory 2a), and #76 Bildtpollen and #90 Tegeler Plate Polder (subcategory 2b, Table A1).

4.2. How sustainable are the different realigned dikes?

Sustainability is a hot and difficult topic, also in flood protection. For example, the Dutch flood risk program aims for sustainable dikes but also acknowledges the difficulty of implementing sustainability (www.hwpb.nl). MR can contribute to sustainable ocean and coastal development and conservation, in line with Sustainable Development Goal 13 Climate Action (United Nations) as a sustainable nature-based flood defence system (Esteves, 2014a; Temmerman et al., 2013). From the numerous aspects associated with sustainability (e.g., Scoones, 2007) we focus on two environmental sustainable aspects of the realigned dike: recycling of existing defence structures and the use of construction material.

When comparing the realigned dike groups, the (2) Existing landward realigned dikes are considered more sustainable than the (1) New dikes based on the recycling of existing defence structures. The use of existing dikes means lower costs and reduced disturbance of the ecosystem so less environmental impact. Especially in (2a) Former hinterland dikes, historical dikes that no longer have a flood protection function can be re-activated by realignment as their flood protection function returns (e.g., Van Loon-Steensma et al., 2014). However, when existing defences are insufficient for flood protection, reinforcements or new dikes are needed. This is relevant at the implementation of new MR schemes, but also for existing MR sites.

To reinforce or build a new dike, construction material is required. The use of local construction material is more sustainable than importing or manufacturing construction material. For example, clay can be mined in saltmarsh pits to reinforce or built a dike and simultaneously rejuvenate the saltmarshes (Marijnissen et al., 2020). Under abundant sediment conditions, these pits can refill over time, after which clay can be mined again (Marijnissen et al., 2020). With regards to manufactured construction material, the Noarderleech dike is most sustainable from the three case studies. It has a clay with grass revetment and only the maintenance path is covered with concrete grass paver blocks (Van Loon-Steensma and Schelfhout, 2013). Initial construction costs are €0.8 million per km lower for a green dike with a shallow profile than for a traditional dike (Van Loon-Steensma and Schelfhout, 2017). When looking at all 90 MRs it is hard to tell which realigned dike group is most sustainable with regards to construction material. Local construction material was used in all realigned dike groups and at all three representative case studies. The old primary dike was reused at the Lillo Potpolder (Table 2) and creek excavation provided construction sediment at the Hedwige-Prosperpolder and the Noarderleech (Table 2). The former polders also provided construction material at Lillo Potpolder and the Hedwige-Prosperpolder (Table 2).

4.3. Limitations of the analysis

Our analysis was a first step in studying how to make realigned dikes greener and thereby facilitate combined flood protection by the realigned dike and adjacent restored saltmarshes. Although a major part of the analysis is based on three representative case studies, our results present some relevant realigned dike characteristics such as dike steepness and revetment. In further research we recommend extending the analysis of the transition between the realigned dike and saltmarshes. More MR projects can be analysed in detail. Additional characteristics can be studied, for instance by taking vegetation surveys of species in the transition zone (higher saltmarsh, dike toe, and lower part of the outer dike slope).

Several limitations of our analysis lead to recommendations to extend the realigned dike groups and overview of MR projects. First, the analysis was limited to Dutch and English literature. As research reports are often hidden in local resources, we recommend searching for literature in other languages as well. The scope of this research was limited to coastal Europe. We recommend exploring realigned dikes globally as for instance de-poldering is also taking place in Bangladesh (Van Staveren et al., 2017). The categorization was limited to coastal MR projects with physical realignment of defences (Esteves, 2014c) where natural tidal exchange is facilitated through breaching, removal or lowering of the original dike. Some excluded projects can be assigned to our realigned dike groups as well, for instance controlled tidal restorations. The Double Dike pilot in the Ems-Dollard Estuary in the Netherlands complies with (1) Newly build landward dikes (e.g., Marijnissen et al., 2021) and the Sébastopol Polder in France can be part of (2) Existing landward dikes of former multiple dike systems (Goeldner-Gianella, 2007a). Realigned dikes in riverine locations can also be added to the overview. For example, the realigned Waal dike at Lent in the Dutch Room for the River project.

4.4. *Recommendations for future managed realignments*

Over the past decades, MR has been evolving as a nature-based alternative to conventional coastal defence schemes (e.g., Bridges et al., 2021; Esteves, 2014a). However, in Europe only relatively small projects have been finalized in a limited number of countries, so far. We recommend extension of realignment size as this may provide future sustainable nature-based flood protection. For instance, Kiesel et al. (2020) show an increase in high water level attenuation with increasing realignment area and Smolders et al. (2015) show more flood wave attenuation along estuaries with larger foreshore areas. One example of an ongoing larger realignment project is the (2a) case study Hedwige-Prosperpolder de-polderisation (465 ha, Van den Hoven et al., 2021). In addition, new realignments are being planned, for instance in Wales (Buser, 2020). When designing a realignment scheme, it is important to keep in mind that although the threat of dike breaching increases with an increase in dike length (Hofstede, 2019), wide saltmarshes fronting the realigned dike reduce the impact of a dike breach (Zhu et al., 2020).

We have three other recommendations to coastal managers for future MR projects. First of all, we recommend to focus on facilitating combined flood protection by the realigned dike and the restored saltmarshes already from the initiation of realignment to enhance integration of saltmarshes in flood protection. To achieve a smooth transition between the dike and adjacent saltmarshes, the realigned dike profile and revetment should be tailored to the local conditions (see examples for the Wadden Sea in Van Loon-Steensma and Huiskes, 2017). Second, although sediment input to each realignment site was beyond the scope of this study, we recommend incorporating sediment availability to assess the potential of future MRs as Liu et al. (2021) recently showed that saltmarsh restoration on formerly reclaimed land is heavily dependent on sediment availability. Third, while MR creates opportunities for nature-based flood protection, it can also locally disadvantage agricultural land surface. So, for each project we recommend to consider local circumstances, involve stakeholders, and balance values.

5. Conclusion

MR is a promising climate adaptation measure for sustainable flood protection, especially in low-lying coastal regions with millions of inhabitants. MR can be seen as a nature-based flood defence zone that combines flood protection by the realigned dike and restored saltmarshes. The aim of this research was to characterize realigned dikes and to indicate the characteristics that offer opportunities for nature-based flood protection. We categorized 90 European coastal managed realignment projects into two realigned dike groups: (1) Newly built landward dikes and (2) Existing landward dikes of former multiple dike systems. The second group has two subcategories: (2a) Former hinterland dikes and (2b) Realignments within summer polders. We consider that the use of existing landward dikes or local construction material make realignment more sustainable. Our results also show that if an accidental breach occurs in the seaward dike of a former multiple dike system, MR can be the solution to provide sufficient flood protection.

From a nature-based flood protection perspective, the presence of the realigned dike is ambiguous. The dike ensures sufficient flood protection of the hinterland which allows geomorphological processes to restore saltmarshes on the formerly reclaimed land. The restored saltmarshes can then provide nature-based flood protection. But a dike also reduces landward accommodation space and thereby limits landward saltmarsh restoration. Our results present the realigned dike characteristics at three representative case studies. We find the targeted and expected saltmarsh restoration at MR does not necessarily result in a greener realigned dike design that suits for combined flood protection with restored saltmarshes. Our analysis shows that the realigned dike and the former reclaimed land can be modified to facilitate nature-based flood protection and promote surface elevation increase seaward of the realigned dike in response to sea level rise. This makes managed realignment a nature-based flood defence zone for now and the future.

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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.

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Appendix. Coastal European managed realignments

Table A.1
Coastal European managed realignments per realigned dike group, case studies in bold. Numbers (#) correspond with Fig. 3. ? is reason for realignment: A = accidental breach, F = flood risk reduction, N = nature restoration, R = recreation, M = military purpose. Area in ha. Main sources are Esteves (2014) and OMReG website, except for *. Only additional sources are listed. [1] Project on the border.

# Name	Location	Country	Year	?	Area	References
1 Newly built landward dikes						
01 Abbotts Hall	Blackwater Estuary	England	2002	F N	84	Dixon et al., 1998; Van Oevelen et al., 2000
02 Allfleet's Marsh	Crouch Estuary	England	2006	N F	133	
03 Anklamer Stadtbruch	Oderhaff	Germany	2004	N F	1750	De La Vega-L. and Stoll-Kleemann, 2015; Rupp-Armstrong and Nicholls, 2007
04 Billwerder Insel	Elbe Estuary	Germany	2008	N	20	
05 Bleadon Levels	Axe Estuary	England	2001	N F	13	White (2015)
06 Brancaster West Marsh	North Sea	England	2002	F N	8	Mossman et al., 2012; National Archives
07 Brandy Hole	Crouch Estuary	England	2002	N	12	Hughes et al., 2009
08 Chowder Ness	Humber Estuary	England	2006	N	15	River Wiki
09 Cobnor Point	Chichester Harbour	England	2013	N F	7	Greenfix
10 Cone Pill	Severn Estuary	England	2001	F	50	
11 Devereaux Farm 1	Hamford Water	England	2010	N	15	EA (2013)
12 Easton Broad	North Sea	England	2020	N F	130	Feretti, 2016 *
13 Geltinger Birk	Baltic Sea	Germany	2013	F N	1000	Schernewski et al., 2018 *
14 Greatham North	Tees Estuary	England	2013	N F	40	EA (2011)
15 Greatham South	Tees Estuary	England	2018	F	30	
16 Het Zwin	North Sea	Be-NL[1]	2019	N	120	Zwin *
17 Horseshoe Lagoon	The Wash	England	2014	A F	8	
18 Jubilee Marsh	Roach Estuary	England	2015	F N	165	RSPB
19 Karrendorfer Wiesen	Baltic Sea	Germany	1993	N F	350	Bernhardt and Koch, 2003; De La Vega-L. and Stoll-K., 2015; Holz et al., 1996
20 Kennet Pans	Firth of Forth Est.	Scotland	2007	N	8	MacDonald et al., 2017
21 Lillo Potpolder	**Scheldt Estuary**	**Belgium**	**2012**	**N R**	**10**	Sigmaplan; Scheldeschorren
22 Medmerry	The Channel	England	2013	FNR	302	Dale et al., 2018; Higuchi et al., 2014
23 Mortagne-sur-Gironde P.	Gironde Estuary	France	1999	A	270	Adapto *
24 Paardeschor	Scheldt Estuary	Belgium	2004	N	12	Van den Bergh et al., 2004
25 Paull Holme Strays	Humber Estuary	England	2003	N F	80	Mazik et al., 2007; DEFRA & Environment Agency, 2002
26 Perkpolder	Scheldt Estuary	Netherlands	2015	N	75	Van de Lageweg et al., 2019; Zeeweringenwiki *
27 Polders of Kruibeke	Scheldt Estuary	Belgium	2013	N	650	Sigmaplan; Cox et al., 2006
28 Salt Fleet Flats Reserve	Thames Estuary	England	2016	N	65	
29 Spadenländer Spitze	Elbe Estuary	Germany	2000	N	8	
30 Stanford Wharf N Reserve	Thames Estuary	England	2010	N R	27	
31 Tollesbury	Blackwater Estuary	England	1995	N F	21	Garbutt et al., 2006; Chang et al., 2001; Van Oevelen et al., 2000
32 Tutshill	Severn Estuary	England	2011	N	2	Google Earth
33 Vega de Jaitzubia	Bay of Biscay	Spain	2004	N	23	Marquiequi and Aguirrezabalaga, 2009
34 Welwick	Humber Estuary	England	2006	N	54	River Wiki
35 Wrauster Bogen	Elbe Estuary	Germany	1991	N	2	
36 Yzer Mouth	North Sea	Belgium	2001	N	50	De Ryke et al., 2004; Hoffman (2004)
2a Former hinterland dikes						
37 Aber de Crozon	Bay of Douarnenez	France	1981	N	87	Bawedin (2004)
38 Alnmouth 1	Aln Estuary	England	2006	F	8	Guthrie et al., 2009
39 Alnmouth 2	Aln Estuary	England	2008	F N	20	Guthrie et al., 2009
40 Bunkervallei, De Slufter	North Sea	Netherlands	2002	N	3	De Leeuw and Meijer, 2003
41 Carmel Polder	The Channel	France	1990	A	30	Dausse and BonisLefeuvre, 2005; Goeldner-Gianella (2007b)
42 Castles dikes	Coquet Estuary	England	2011	N	8	
43 Cwm Ivy	Loughor Estuary	England	2014	A N	39	National Trust
44 Freiston	North Sea	England	2002	F N	66	Symonds and Collins, 2007; Kiesel et al., 2020, 2019
45 Graveyron Polder	Arcachon Bay	France	1996	A	23	Adapto; Goeldner-Gianella et al., 2015 *
46 Great Orcheton Fields	Erme Estuary	England	2007	A	24	White (2015)
47 Groene Hoek, De Slufter	North Sea	Netherlands	2002	N	13	De Leeuw and Meijer, 2003
48 Groene Strand	Wadden Sea	Netherlands	1996	N	23	De Leeuw and Meijer, 2003; Abrahamse (1997)
49 Hahnöffersand	Elbe Estuary	Germany	2002	N	104	Morris (2011)
50 Havergate Island	Ore Estuary	England	2000	N	8	RSPB
51 Hedwige-Prosperpolder	**Scheldt Estuary**	**Be-NL[1]**	**Future**	**N**	**465**	Soresma, 2013; Van den Bergh and Mertens, 2005; Van den Hoven et al., 2021*
52 Hesketh Out Marsh E	Ribble Estuary	England	2017	N F	160	RSPB
53 Hesketh Out Marsh W	Ribble Estuary	England	2008	N F	180	MacDonald et al., 2017
54 Horsey Island	Taw Torridge Est.	England	2017	A N	87	
55 Ile Nouvelle	Gironde Estuary	France	2000	A	265	Adapto *
56 Kleinensieler Plate	Weser Estuary	Germany	2000	N	58	
57 Kreetsand	Elbe Estuary	Germany	2015	FNR	30	IBA Hamburg
58 Kroon's polders	Wadden Sea	Netherlands	1996	N	85	De Leeuw and Meijer, 2003
59 Lantern Marsh North	Ore Estuary	England	1999	F N	29	
60 Lytchett Fields	Poole Harbour Est.	England	2012	A	23	
61 Malprat island	Arcachon Bay	France	2002	A	12	Goeldner-Gianella et al., 2015; Adapto *
62 Nigg Bay	North Sea	Scotland	2003	N	25	Elliot (2015)
63 Northey Island		England	1991	F	1	Nature, 1994; Van Oevelen et al., 2000

(continued on next page)

Table A.1 (*continued*)

# Name	Location	Country	Year	?	Area	References
	Blackwater Estuary					
64 Pawlett Hams	Parret Estuary	England	1994	F	5	Wolters et al., 2005
65 Polder Friedrichshagen	Bay of Greifswald	Germany	1999	N F	90	De La Vega-Leinert and Stoll-Kleemann, 2015
66 Skinflats	Estuary	Scotland	2018	N R	10	EcoCo; MacDonald et al., 2017
67 Steart Marsh	Parret Estuary	England	2014	F N	262	Pontee and Serato, 2019
68 Sundische Wiese	Baltic Sea	Germany	2014	N F	940	De La Vega-Leinert et al., 2018, 2015 *
69 Thornham Point	Chichester Harbour	England	1997	N F	7	Google Earth
70 Titchwell Marsh	North Sea	England	2011	F	11	RSPB
71 Trimley Marsh	Orwell Estuary	England	2000	N	16,5	Wolters et al., 2005
72 Verdronken land van Saeftinghe	Scheldt Estuary	Netherlands	1570	M A	3600	Soresma (2013) *
73 Verdronken Zwarte Polder	North Sea	Netherlands	1802	A	89	Van Dort and Leusink, 1998; Het Zeeuwse Landschap *
74 Viggelso	Odense Fjord	Denmark	1993	N	66	Fenger et al., 2008
75 Ynys-hir	Dyfi Estuary	England	2010	N F	6	
2b Realignments within summer polders						
76 Bildtpollen	Wadden Sea	Netherlands	2009	N	45	Bakker et al., 2014
77 Cappel-Süder-Neufeld	Weser Estuary	Germany	1999	N	27	Saathoff and Lange, 2012 *
78 Dorumer Sommerpolder	Wadden Sea	Germany	2001	N	4	
79 Geddal Strandenge	Limfjord	Denmark	1992	N	140	Fenger et al., 2008
80 Hauener Hooge	Wadden Sea	Germany	1994	N	80	
81 Holwerder zomerpolder	Wadden Sea	Netherlands	1989	N	28	Van Oevelen et al., 2000
82 Ketenisseschor	Scheldt Estuary	Belgium	2002	N F	36	Esteves (2014); Van den Bergh et al., 2005a
83 Langeooger Sommerpolder	Wadden Sea	Germany	2004	N	215	Barkowski et al., 2009
84 Lütetsburger Sommerpolder	Wadden Sea	Germany	1982	N	15	Mai and Zimmerman, 2002
85 Noarderleech	**Wadden Sea**	**Netherlands**	**2001**	**N F**	**135**	Esselink et al., 2015; Bakker et al., 2001; Van Loon-Steensma and Huiskes, 2017
86 Peazemerlannen	Wadden Sea	Netherlands	1973	A	164	De Leeuw and Meijer, 2003; Wolters et al., 2005; Van Oevelen et al., 2000*
87 Pepelow	Salzhaff Bay	Germany	2002	N	120	De La Vega-Leinert and Stoll-Kleemann, 2015
88 Sieperdaschor	Scheldt Estuary	Netherlands	1990	A	100	Eertman et al., 2002; Van Oevelen et al., 2000 *
89 Sommerpolder Wurstre	Wadden Sea	Germany	2007	N	145	
90 Tegeler Plate Polder	Weser Estuary	Germany	1997	N	150	

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