



Loss of shallow water physiotope areas in tidal estuaries of the North Sea since the nineteenth century

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Abstract

Purpose The main aim of this study was to quantify changes in shallow water physiotopes in the North Sea estuaries of Elbe, Humber, Scheldt, and Weser and to collect information on engineering activities which influenced the estuarine hydrology and potentially the spatial range of physiotopes, both between the nineteenth century and present day. A second aim was to provide a database on the recent physiotope distribution for the assessment of future interventions on these estuaries.

Methodically Physiotopes were defined by water depth and salinity. The area of the sub-, supra-, and intertidal physiotopes was calculated from digitised maps from different times since the nineteenth century. The spatial changes were opposed to the dates of implementation of the hydraulic engineering activities.

Results From the nineteenth century onwards, the shallow water physiotopes of Elbe, Sea Scheldt, and Weser decreased spatially between 4 and 30%, whereas for the Humber estuary the areas have remained stable. The loss of areas was particularly located in the inner estuaries and concerned mostly freshwater physiotopes. The oligohaline and mesohaline zones exhibited less of a reduction in size, although, in the same order of magnitude, while the area of polyhaline physiotopes remained nearly unchanged.

Conclusion The loss of physiotopes which occurred mainly in the freshwater and oligohaline zones is important because physiotopes host different salinity-dependent biological communities. This loss of physiotopes could be observed after the implementation of hydraulic engineering projects, which could have led to higher current velocities, further upstream tidal penetration and very likely a corresponding shift of the salt-/freshwater interface upstream. All these effects altered the physiotope areas of the estuaries, except of the Humber estuary. The Humber had been modified to its today's shape essentially before the nineteenth century. Nevertheless, the data describing the recent size of physiotopes provide a reference base for the assessment of future interventions in the estuaries of Elbe, Humber, Sea Scheldt, and Weser.

Keywords Estuary · Loss of physiotope areas · Elbe · Humber · Scheldt · Weser

1 Introduction

North Sea estuaries represent highly dynamic environments and host specialised flora and fauna which have to cope with fluctuating conditions in relatively short time scales such as large salinity and temperature gradients, turbidity, and tidal currents. Within such a dynamic environment, various physiotopes and habitats exist in close neighbourhood, building a valuable and sensitive ecosystem of high connectivity (Elliott et al. 2019). Besides the term physiotope, the concepts habitat, ecotope, and biotope are often used to identify biological units of an ecosystem. In this study, the term physiotope solely defined by abiotic parameters (Farina 1998) was applied to describe such units. The reason for

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this is that the terms biotope, habitat (Natuhara 2006), and ecotope (Forman 1995) require information about biological factors which were not available for the time of the reference scenario or at the middle of the twentieth century.

Additional to their ecological value, estuaries are of high economic relevance with important harbour cities and touristic infrastructure (e.g. Meire et al. 2005; Van der Belt and Costanza 2011; Kennish 2019). This exerts pressure on such ecosystems, and against this background, Kennish (2019) grouped anthropogenic activities on estuarine environments into stressors that (1) change water quality, that (2) driven by physical factors which can have an impact on physiotopes, and (3) both at the same time. Such physical engineering activities include the construction of embankments, dykes and flood barriers, as well as the modification of estuaries by dredging fairway channels to provide safe navigation but often requiring long-term maintenance dredging. These interventions alter the hydrology and can influence ecosystems in an estuary (e.g. Meire et al. 2005; Dugan et al. 2011; Kennish 2019; Vauclin et al. 2020).

For example, the channelization of streams frequently applied in combination with the construction of groynes and dams for impoundments often results in an increase of the flow velocity (Kennish 2019). Such higher currents in a channelized estuary can change the patterns of erosion and sedimentation. From a civil engineer's perspective this was often a desired effect (e.g. Franzius 1888) but inevitably had led to changes in the grainsize distribution of sediments (Franzius 1888; Hjulström 1935; Vauclin et al. 2020). In their study, Vauclin et al. (2020) investigated the influence of infrastructures such as dams, dikes, and groynes on sedimentation patterns. Interpreting grain size data from cores, the authors observed that after the implementation of such infrastructure homogenous sediments had replaced more diverse substrates. This is of relevance because the sediments provide the substrate for physiotopes and habitats (Kusnierz and Sivers 2018) of an estuary. Another effect of channelizing estuaries and higher currents is often an increased concentration of suspended matter like in the Humber (Morris and Mitchell 2013). Consequently, such a combination of higher currents and changing sediment grain size effects the occurrence of physiotopes (Kennish 2019). In addition, the diking of supratidal areas inevitably reduced the areas of many physiotopes directly (Kennish 2019). However, directly does not mean at once. Townend (2004) worked on changes in estuaries and figured out that the extent of physiotopes can react on hydraulic engineering activities on different timescales.

Considering this context, it was the aim of this study to quantify temporal changes in the extent of shallow water physiotopes in a series of North Sea estuaries, including the Elbe, Humber, Scheldt, and Weser. There are many studies which

focus on wetland loss due to anthropogenic impacts such as Declerck et al. (2016) or Davidson (2014). Studies partly integrating intertidal areas can be found as well (e.g. Mander et al. 2007) but rare are studies integrating shallow water areas (e.g. Meire et al. 2005). However, our study integrates supratidal, intertidal, and subtidal physiotopes and, additionally, considers their position in the estuary with respect to salinity zones ranging from freshwater to polyhaline. We consider this to be important because these areas distinguished according to water level and salinity provide living space to different biological communities (e.g. Kennish 2019). The authors think that these physiotopes should be distinguished to better describe and assess changes on estuarine ecosystems.

Within this study, physiotope areas were quantified for different times and compared to a reference scenario in the nineteenth century prior to extended engineering activities in the estuaries. Through a comprehensive analysis of maps from different times compared with the time of implementation of engineering activities, the influence of such activities against the reference scenario was quantified. Additionally, the calculated recent extent of physiotopes serves as a tool to assess the impact of future changes.

2 Methods

Engineering activities with potential influence on hydraulic conditions in the estuaries like diking, land reclamation, channelizing anabranches, deepening fairways, cutting of tributaries, and constructing weirs were listed chronologically because changes on the hydrology can influence the sedimentation (Hjulström 1935).

Another focus was to map and measure the size of living space for organisms in the estuaries. Such living space is distinguished into units such as biotopes, habitats, or physiotopes. While the terms biotope, habitat (Natuhara 2006), and ecotope (Forman 1995) require a range of descriptive parameters including information about biological factors, the term physiotope is defined exclusively by abiotic criteria (Farina 1998). Since for the time of our reference scenario at the end of the nineteenth century and for the time at the mid of the twentieth century only abiotic parameters were available, the term physiotope was applied in this study to describe ecological units.

2.1 Time steps

We compared the extent of physiotopes within the four estuaries at three times: (1) at the end of the nineteenth century/early twentieth century, (2) at the mid of the twentieth century, and (3) in recent times at the end of the twentieth century. The situation at the end of the nineteenth century/

Table 1 Development of container vessels acc. to Tran and Haasis (2015)

Generation of vessels	Maximum number of containers	Length (m)	Width (m)	Draught (m)
1956	500–800	137	17	9
1970	1000–2500	215	20	10
1985	300–4500	290	32	12.5
1988	4–6000	300	40	13
2000	6–8500	340	43	14.5
2006	11–16,000	397	56	15.5
2013	18–21,000	400	59	16

the early twentieth century was used as reference status prior to most changes due to hydraulic engineering construction. For the reference scenario information on water depth in the respective maps were needed. A time step after 1950 in the middle of the twentieth century was the next choice because after the 2nd World War bigger ships were designed, requiring greater water depth (Table 1).

The age of the used nautical charts differed in accordance with the times of mapping the respective estuaries and their fairways (Table 2). The maps, nautical charts and aerial photographs (see detailed reference list in the annex) were digitised and geo-referenced using ArcGIS version 10.0. The extent of physiotopes within different salinity zones along the rivers was calculated by creating polygons. The systematic mistake for the calculated areas was below 0.15%, calculated as deviation of the sum of all areas in a salinity zone divided by the area of the salinity zone before separation into respective areas.

2.2 Salinity zonation according to the Venice system (Caspers 1959)

Each investigated estuary was subdivided into salinity zones according to the Venice system (Caspers 1959). The basis to this was respective median values of chlorinity over 6 years (2004–2009) calculated from measurements within routine monitoring programmes along the rivers (Geerts et al. 2012). So freshwater, oligo-, meso-, and polyhaline zones were distinguished (Table 3). This zonation was also applied retroactively to the previous time steps.

Table 2 Age of nautical charts considered for calculating physiotope areas

	End of nineteenth century/ early twentieth century	Mid of twentieth century	Recent time/end of twentieth century
Elbe	1900	1950	1992–95
Humber	1910/24	1975	2008
Sea-Scheldt	1880/87 and 1930	1960/72	2000
Weser	1860/87	1951/52 and 1961/62	2005–2008

2.3 Physiotope areas

Within each salinity zone, physiotope areas were distinguished at different depth intervals, including below mean low water level (MLWL), mean high water level (MHW), and above MHW, e.g. sub-, inter-, and supratidal areas; synonymously, intertidal areas are often called tidal flats (Table 4). Within the supratidal areas marshes, summer polder, and stagnant water were distinguished. ‘Marsh’ was characterised as a supratidal area without a summer dike which is a dike lower than storm surge water levels, and ‘summer polder’ represents areas protected by a summer dike and ranged towards the main dike (Schuchardt et al. 2007). The ‘stagnant water’ classification is related to physiotopes located in dike forelands. Unfortunately, the information needed to determine ‘stagnant water’ and the ‘summer polder’ physiotopes were only available for the Sea Scheldt and the Weser estuaries.

3 Engineering activities with influence on the hydrology of the estuaries of Elbe, Humber, Schelde, and Weser

In geological time scales, North Sea estuaries have changed as the result of climate change after the Weichselian ice age (appr. 115,000 until 11,700 years before present (Cohen et al. 2013)). The melting of glaciers and inland ice shields flooded the North Sea basin due to a sea level rise of approximately 120 m. Since the commencement of sea-level monitoring in the nineteenth century, the measured relative sea level rise has comprised climatic and isostatic movements in the North Sea (e.g. Kiden et al. 2002), but with effects found to differ regionally. For example, in the German Bight, the mean high-water level rose approximately 25 cm while the mean low-water level increased by 10 cm/100 years since 1890 (Fickert and Strotmann 2007). For the Humber area, a minor increase in the rate of relative sea-level rise has been assessed at 4 mm yr⁻¹ up to 12 mm yr⁻¹ by end of the twentieth century (Environmental Agency 2011). Additionally, the patterns of precipitation can change, with such changes influencing the hydraulic situation in estuaries (Atkins 2002; Schuchardt and Schirmer 2005; Meire et al. 2005).

Table 3 Lateral extension of salinity zones of the estuaries of Elbe, Humber, Scheldt, and Weser based upon the Venice system (Geerts et al. 2012)

Salinity zone (PSU) ^c	Elbe (km) ^a	Weser (km) ^a	Schelde (km) ^a	Humber (km) ^{a,b}
Freshwater (<0.5)	0–91	0–44	0–58	Trent: 0–45; Ouse till confluence with the Aire: 0–34 km
Oligohaline (0.5–5)	91–118	44–69	58–89	Trent: 45–85 Ouse 34–60
Mesohaline (5–18)	118–141	69–84	89–116	Humber: 60–93
Polyhaline (18–30)	141–171	84–119	116–160	Humber: 93–123

^akm downstream from the inland tidal boundary (e.g. a weir)^bThe Humber starts with kilometre '0' at Naburn Weir in the river Ouse. Downstream the Ouse and river Trent converge to be the Humber, starting there with the kilometre number 60^cPSU practical salinity unit

In addition to such naturally occurring processes, the four estuaries have been historically modified by hydraulic engineering activities, mainly land reclamation, to protect the landscape and human settlements from flooding and further measures to allow and maintain navigation. An important recent driver for change has been the development of increased vessel sizes which require maximum draughts of up to 16 m in the main fairways (Table 1), necessitating engineering work to ensure sufficient fairway depth. In addition to deepening of waterways, many tributaries were cut off from the tidal regime by the installation of weirs (Table 5). This combination of interventions has led to changes in hydrology resulting in increasing tidal ranges (Fig. 1) along the estuarine system (e.g. Franzius 1888; Meire et al. 2005; Schuchardt et al. 2007). The effects on the hydrology of estuaries from engineering measures to protect the land from flooding and to improve navigation are described in numerous publications (e.g. Franzius 1888; Meire et al. 2005; Elsebach et al. 2007; Fickert and Strothmann 2007; Schuchardt et al. 2007; Elliott et al. 2019; Vauclin et al. 2020).

In Table 5 engineering activities which could have had an impact on the hydrology of the investigated estuaries are listed chronologically. Additionally, the point in time of the maps that were used to calculate the extent of physiotopes

is inserted as well to see which maps can present the effects of implemented hydraulic engineering activities on the physiotopes.

4 Spatial change of littoral physiotopes

Over time the overall size of the shallow water physiotopes in the estuaries of the Elbe, Sea Scheldt, and Weser showed decreases in a range between 4 and 36%, whereas the respective areas of the Humber estuary remained quite stable since the nineteenth-century baseline (Table 6). Since the physiotope types are distinguished with a vertical component with respect to the water depth and a horizontal component with respect to an increasing salinity towards the mouth of the estuary, first, both aspects are presented separately.

4.1 Extent of physiotopes distinguished with respect to water depth from the nineteenth century towards the end of the twentieth century

Without consideration of salinity along the contemporary estuaries more than half of the shallow water, physiotope areas are covered by subtidal physiotopes. The values range from 69% in the Sea Scheldt and 50% in the Elbe while the extent of intertidal areas varies between 17% in the Sea Scheldt and 40% in the Weser. So, the supratidal areas cover less than 12%. Comparing this with the values in the nineteenth century, it becomes obvious, that except of the Humber the areas of the littoral physiotopes decreased; however, mainly at the expense of supratidal areas which shrunk by more than half of the areas; especially in the Sea Scheldt the loss of the supratidal areas reached a value of 79% (Table 6).

The losses in the intertidal were below 11% and the changes in the subtidal varied in wide ranges from close to zero in the Sea Scheldt up to 7% in the Elbe. But by distinguishing the subtidal physiotopes into the parts deep water, slope, and shallow water it becomes obvious that the overall category 'subtidal' comprises opposing trends. For

Table 4 Classification of physiotope types

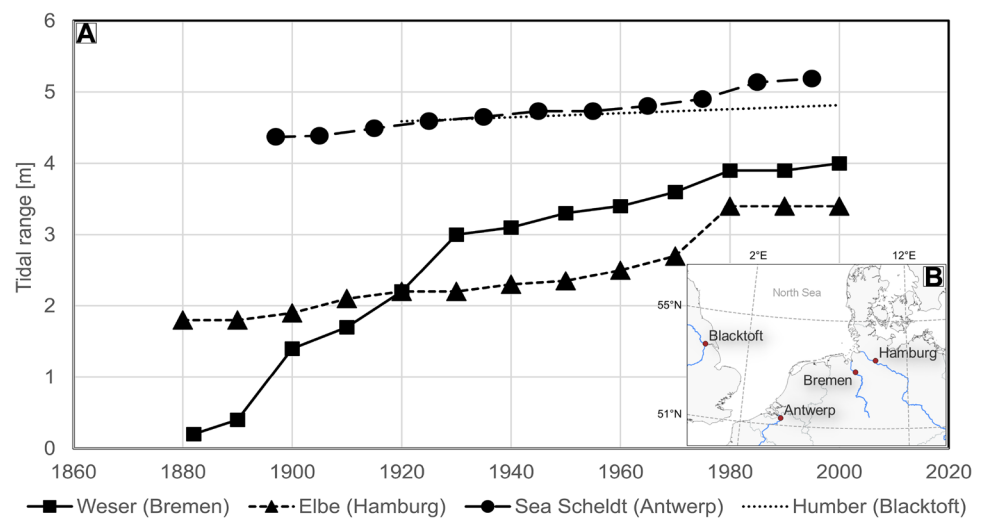
Water depth	Classification according to Elsebach et al. (2007)	Physiotope types
> MHWL	Supratidal	Stagnant waters Summer polder Marsh
< MHWL > MLWL	Intertidal	Tidal flat
< MLWL	Subtidal	Shallow (< MLWL to –2 m) slope (–2 m to –5 m < MLWL) deep (more than –5 m < MLWL)

Table 5 Hydraulic engineering activities in chronological order with potential influence on the hydrology of the estuaries

	Elbe	Humber	Schelde	Weser
until eighteenth century	Land reclamation with diking started before fourteenth century ^g	Land reclamation with diking started at Roman times and increased since the eleventh century. Very intense during the seventeenth century ^b ; constructing tidal weirs Gainsborough 1794 (Trent), 1741 in Naburn (Ouse)	Land reclamation with diking since early middle-age (appr. 1,000 AD) ^h	Land reclamation with diking started before eleventh century ^e
	Deepening fairways occasionally since fifteenth century ^d	At the start of the eighteenth century, the modern form of the estuary had been established ^c		
	Maps for reference scenario			
Nineteenth century	Channelling the fairway: regularly since nineteenth century, increased intensity since 1896 ^d	Land reclamation still occurring but at a much-reduced rate ^e	Deeping main fairway	Channelling : intense since 1885
	Deepening main fairway , 1843 at 4.5 m ^{a,d}			Deepening main fairway , 1887 at 5 m ^{a,e}
Twentieth century	Cutting off tributaries since 1950 ^d : Dove Elbe, Süderelbe, Lühe, Seeve, Oste, Pinnau, Krük-kau, Schwinge, Illmenau, Stör	Land reclamation still occurring but with compensatory habitat now being required for such projects ^b		Tidal weir Bremen (1906–1913)
	Maps displaying the extent of physiotoxes in the middle of the twentieth century			
	Tidal weir Geesthacht (built in 1960)		Cutting off meanders and straightening the fairway tidal weir in Gent (Merebeke built in 1969)	Cutting off tributaries since 1960's: Geeste Lesum, Hunte, Ochtrum, Drepte, Lune, Deepening main fairway, 1980 at 9 m ^{e,a}
	Deepening main fairway , stepwise to a depth at 14.5 ^a m in 2000 ^d		Deeping main fairway until 2009: 14.5 m ^a	Deepening main fairway 1998 partly to 14.5 m ^{f,a}
	Maps displaying the extent of physiotoxes at the end of the twentieth century			

^awaterdepth with respect to lowest astronomic tide (LAT); References cited within Table 2: ^bMander et al. (2007); ^cMorris and Mitchell (2013); ^dFickert and Strotmann (2007); ^eSchuchardt and Schirmer (2005); ^fLucker et al. (1995); ^gFreitag et al. (2007); ^hMeire et al. 2005

Fig. 1 Tidal range (A, main figure) from the nineteenth century to recent times at monitoring gauges in estuaries (data from Schuchardt et al. (2007) for Elbe and Weser and Meire et al. (2005) for the Sea Scheldt and for the Humber from ABP-mer (2004)). The location of all estuaries can be found in the map (B)



example, in the Sea Scheldt, the development in the subtidal was mainly related to the increase of deep water whereas slope and shallow water physiotopes as part of subtidal areas

decreased. Altogether, a loss of intertidal areas was calculated like in the Weser and the Elbe.

Table 6 Extent of physiotopes (ha) from nineteenth century until present times—summing up the areas of sub-, inter-, and supratidal

		Nineteenth century	Mid-twentieth century	End of twentieth century	Change nineteenth to end of twentieth century (%)
Σ Elbe		101,944	90,422	84,175	−17
Subtidal	Deep water	33,442	35,632	33,423	0
	Shallow water	12,359	10,283	8870	−28
Intertidal		34,300	25,771	33,000	−4
Supratidal		21,843	18,736	8882	−59
Σ Humber		28,422	28,130	28,216	−1
Subtidal		17,394	17,206	16,298	−6
Intertidal		10,142	10,291	11,078	9
Supratidal		887	632	840	−5
Σ Sea Scheldt^a		7516	5613	4834	−36
Subtidal	Deep water	1659	1635	2074	25
	Slope	1012	968	823	−19
	Shallow water	676	638	432	−36
Intertidal		929	889	824	−11
Supratidal	Marsh	1470	1021	682	−54
	Summer polder	1720	398	0	−100
	Stagnant water	51	64	0	−100
Σ Weser		105,289	101,044	100,716	−4
Subtidal	Deep water	56,917	26,202	24,294	−5 ^b
	Slope	no data	15,924	16,618	
	Shallow water	no data	10,869	13,176	
Intertidal		40,764	43,255	40,322	−1
Supratidal	Marsh	7609	4793	3834	−50
	Summer polder	No data	No data	2391	
	Stagnant water	No data	No data	81	

The numbers in bold mathematically represent the sum of the "subtidal", "intertidal" and "supratidal" numbers

^aHere only the Sea Scheldt without polyhaline and part of the mesohaline zone of the Western Scheldt's estuary is considered due to data availability. So, data do not represent the overall estuary which would cover an area of c 35,000 ha

^bCalculated relative to the sum of subtidal areas, comprising 'deep water', 'slope', and 'shallow water' areas

4.2 Change of physiotopes distinguished with respect to salinity zones from the nineteenth century towards the end of the twentieth century

Considering the salinity reveals that the greatest loss of physiotopes took place along the freshwater and oligohaline zones. Since the nineteenth century in the Elbe, the Sea Scheldt, and the Weser between 33 and 56% of the freshwater areas were lost. The oligohaline zones showed a spatial reduction in a comparable range of 38 to 22%. The size of the mesohaline zone decreased to a lesser extent between below 18% whereas areas of polyhaline physiotopes remained nearly unchanged (Table 7).

4.3 Change of physiotope areas in freshwater and oligohaline zone

The loss of freshwater areas in the Elbe, the Sea Scheldt, and the Weser estuary summed up to many thousands of hectares (Fig. 2); however, allocated differently with respect to water depth. While the Weser showed a loss distributed equally to all physiotope types, the freshwater zone of the Sea Scheldt was characterised by an enormous loss of supratidal areas,

and in the Elbe, a gain of intertidal areas was compensated by loss in supratidal and intertidal.

The oligohaline zone of the Elbe estuary was dominated by a decrease in about 70% of the supratidal area accompanied by an increase of intertidal (Fig. 3). Subtidal areas decreased as well. The oligohaline zone of the Weser showed that the subtidal areas decreased by 50%, with supratidal also decreasing while the intertidal physiotope types showed a slight increase in extent. Again, the Sea Scheldt was dominated by a significant loss of supratidal areas.

5 Discussion

This study quantified the change of littoral physiotopes in estuaries opposed to engineering activities with potential impact on the hydrology of estuaries. In a similar approach based on more than 180 reports Davidson (2014) showed that more than 50% of wetlands were lost worldwide since the eighteenth century. On a more detailed scale, Decler et al. (2016) compared the spatial extent of habitats in Flanders at different times from 1950 towards 2005. Both, Davidson (2014) and Decler et al. (2016) remarked that estimations on

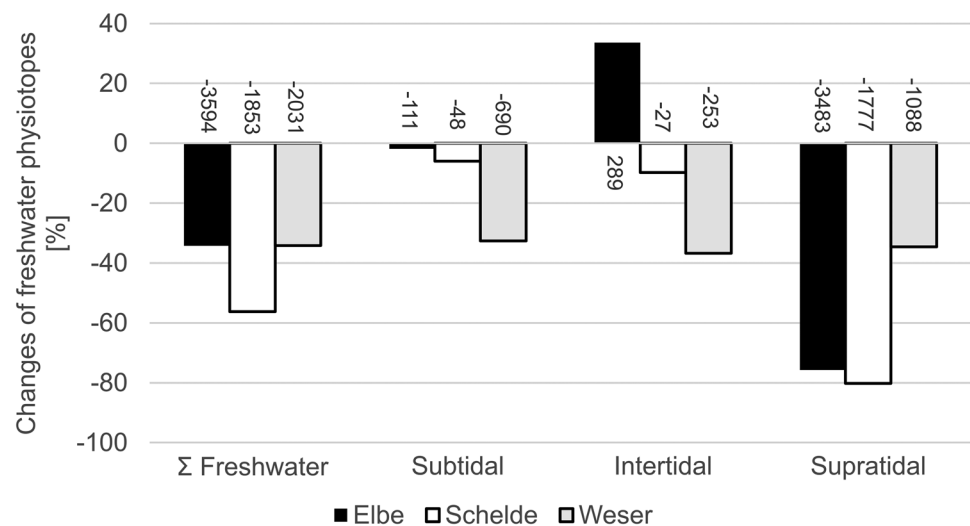
Table 7 Extent of physiotopes (ha) in the estuaries subdivided in salinity zones according to Caspers (1959)

	End of nineteenth/early twentieth century	Mid of twentieth century	End of twentieth century	Change from nineteenth to end of twentieth century (%)
Elbe				
Freshwater	10,481	8982	6886	− 34.3
Oligohaline	15,286	15,686	9553	− 37.5
Mesohaline	47,376	37,910	38,905	− 17.9
Polyhaline	28,802	27,842	28,828	0.1
Σ Elbe zones	101,945	90,420	84,172	− 17.4
Humber				
Mesohaline	8704	8578	8585	− 1.4
Polyhaline	19,719	19,552	19,631	− 0.4
Σ Humber zones^a	28,422	28,130	28,216	− 0.7
Sea Scheldt^b				
Freshwater	3297	1829	1460	− 55.7
Oligohaline	1282	1175	997	− 22.2
Mesohaline	2937	2609	2413	− 17.8
Σ Sea Scheldt zones^b	7516	5613	4870	− 35.2
Weser				
freshwater	5943	3761	3912	− 34.2
oligohaline	6211	4494	4524	− 27.2
mesohaline	11,014	10,386	9990	− 9.3
polyhaline	82,121	82,404	82,288	0.2
Σ Weser zones	105,290	101,044	100,714	− 4.3

^aThe oligohaline and freshwater zones of the Humber estuary lay in the tributaries such as Ouse and Trent. Due to the lack of data, they could not be considered

^bThe Sea Scheldt was considered without polyhaline and part of the mesohaline zone of the Western Scheldt's estuary

Fig. 2 Changes of freshwater physiotope areas (%) from the nineteenth century compared to recent times (the numbers integrated in the graph are changes expressed in hectare)



area loss, subdivided into different habitat types are very rare in literature. However, an evidence-based management of an estuary needs exact data, e.g. on the extent of its physiotope. Accordingly, our project provides data on a detailed scale for four estuaries in the North Sea region and their development since the end of the nineteenth century. The digitization of sea charts of the estuaries but at different times has enabled us to quantify the development of areas subdivided into supratidal, intertidal and subtidal. Considering the salinity combined with the water depth the study has facilitated a comparison of physiotope patterns over different periods and for different salinity zones along the estuaries.

The consideration of the salinity zone is an important information because the loss of areas was most distinct in freshwater and oligohaline zones. Our calculated loss might be a minimum loss because over time, straightening and deepening of fairways could have led to a movement of the saline waters upstream (e.g. Schuchardt et al. 2007).

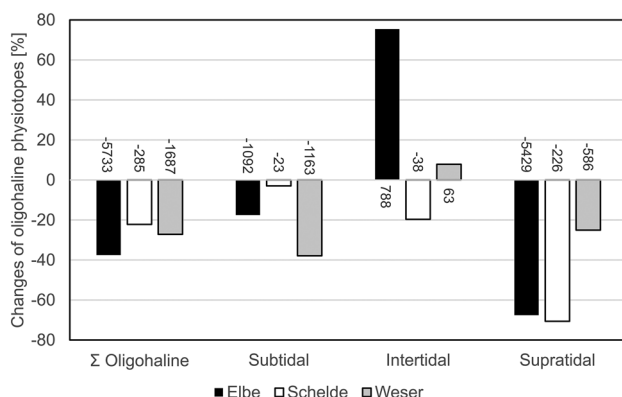


Fig. 3 Change of physiotope areas (%) in the oligohaline zones from the nineteenth century compared to recent times (the numbers integrated in the graph are changes expressed in hectare)

Accordingly, it can be assumed that upstream freshwater or oligohaline zones had a wider extent in times prior to engineering interventions altering the hydraulic conditions and our calculated losses tend to underestimate the changes.

Another focus of this study was to see whether hydraulic engineering activities influenced the distribution and extent of physiotope. It is known that, e.g. the straightening of branches in an estuary to a main fairway and deepening of such fairways to ease the navigation of deep vessels has caused higher tidal propagation and increased tidal range. This had been shown for the Elbe (Fickert and Strotmann 2007; Kerner 2007), the Weser (Schuchardt et al. 2007) and the Sea Scheldt (Meire et al. 2005). In the studied estuaries most of those engineering activities started in the second half of the nineteenth century except of the Humber (Table 5).

In the Humber, as summarised by Morris and Mitchell (2013), most changes on the estuary's shape had been taken place between Roman times and the beginning of the eighteenth century. As a consequence, the area of tidal Humber has been reduced from over 90,000 ha to an area of approximately 30,000 ha since the early 1700s (Boyes and Elliott 2006). Hence, the maps of the physiotope along the Humber evaluated in this study considered a time span after most engineering activities with an impact on the extent of littoral physiotope. Nevertheless, the data represent the actual distribution of physiotope and they can be applied as a reference to assess spatial changes of physiotope areas of the Humber in the future.

5.1 Overall trends considering physiotope

The data show a loss of shallow water areas within most of the investigated estuaries except the Humber. In the other estuaries investigated in this study the biggest relative loss

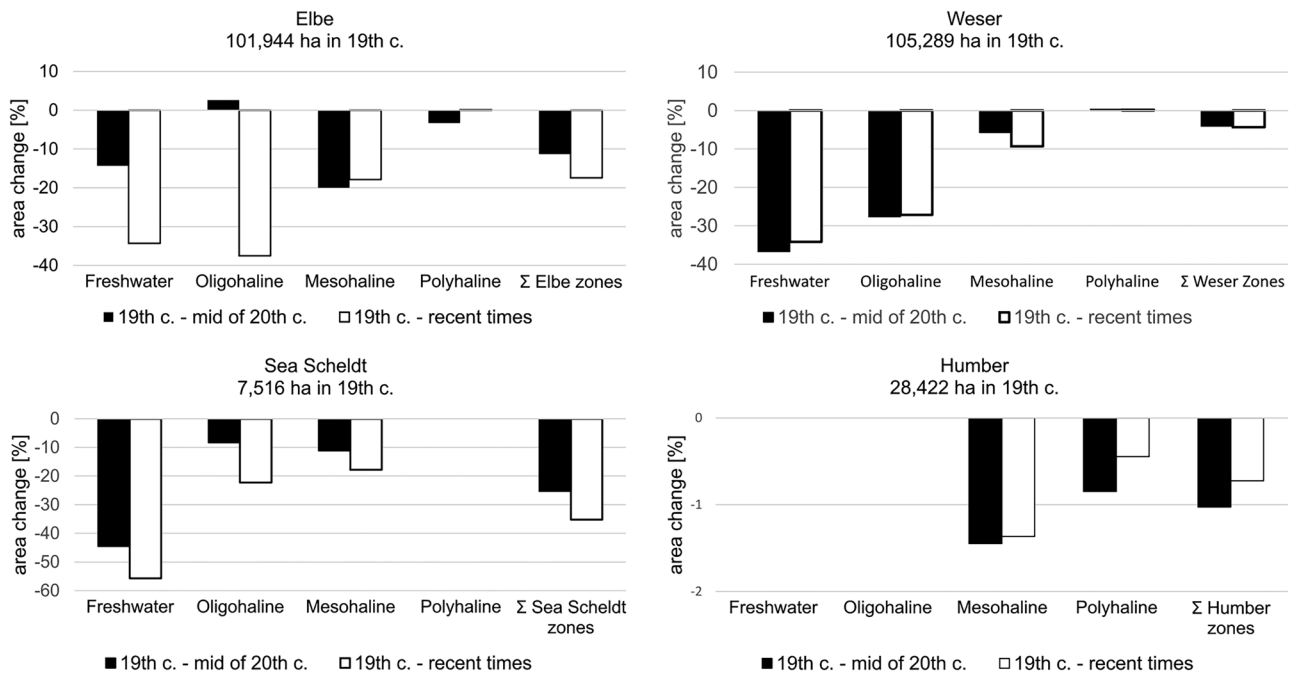


Fig. 4 Changes (%) of littoral physiotope areas in salinity zones compared to their extent end of the nineteenth century. The Elbe, Sea Scheldt and Weser show the highest losses of areas in the inner zones

(freshwater and oligohaline) of the estuaries, and closer to the mouth (mesohaline) less areas diminished

was observed from the freshwater and oligohaline and to a lesser extend in the mesohaline zone (Fig. 4). In contrast, the polyhaline areas remained relatively stable in extent over time.

Historically most harbours were developed further upstream in the estuaries where better shelter against storms was naturally provided. This advantage of upstream harbours

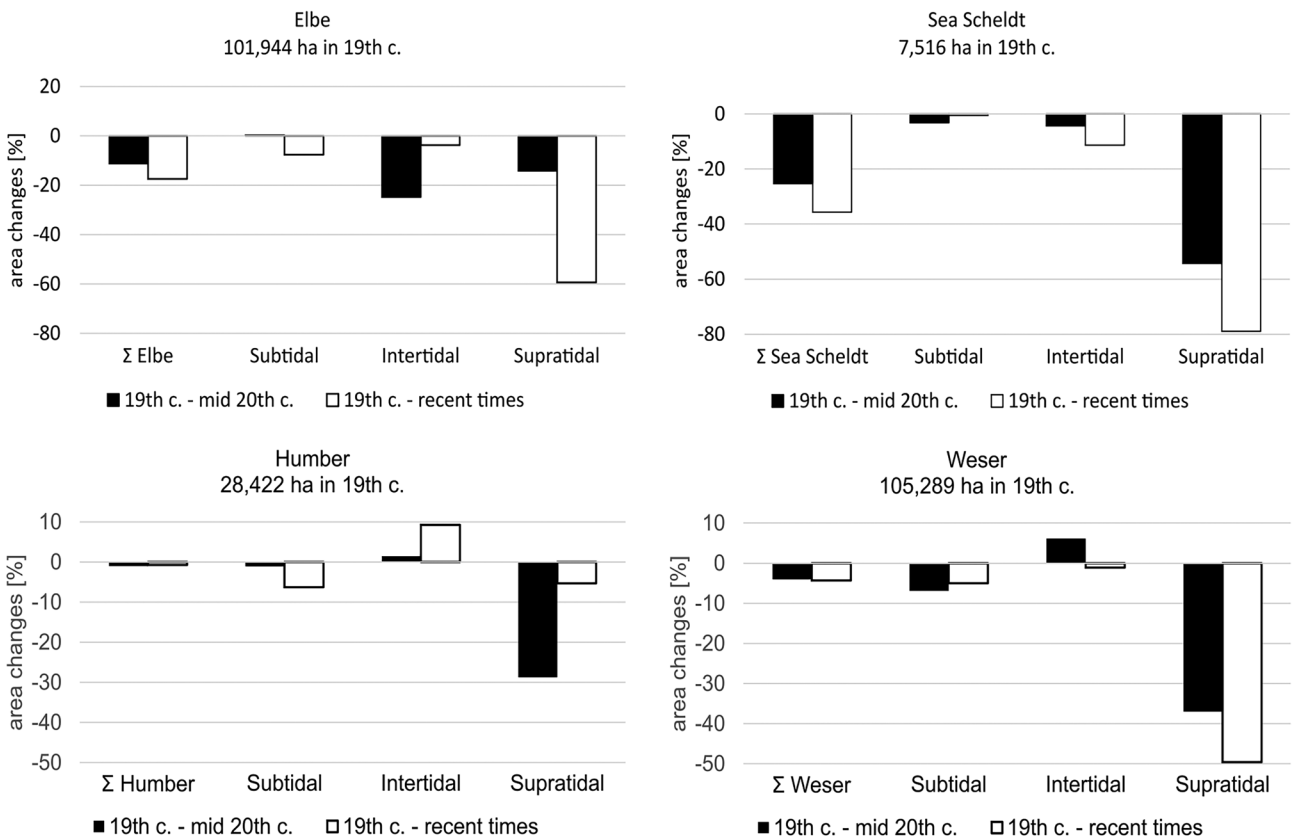


Fig. 5 Development of littoral physiotypes from the end of the nineteenth century to recent times. In all estuaries, the supratidal shows the highest diminishing

became less important in the twentieth century when the vessels became larger, and ultimately the upstream position of these ports often became a problem or constraint, as larger vessels less affected by storms also required greater water depths and widths. To guarantee the access of vessels to important upstream harbour infrastructure in the estuaries, capital and maintenance dredging practices have been adopted. In the course of capital dredging, the channels in the estuaries were straightened and deepened. Both factors brought about hydrological changes such as higher currents and increasing tides upstream and due to the position of the important harbours in the freshwater or oligohaline zones, the upstream zones were more effected than downstream parts of the estuary.

A comparison of the different littoral areas showed that the supratidal physiotope areas decreased the most (Fig. 5). Such a loss of supratidal areas could be attributed to the construction of dikes. Reasons for diking were land reclamation and later, the protection of arable land and infrastructure from flooding. Due to data availability being only for the Sea Scheldt, the supratidal areas could be distinguished in sub-categories (Fig. 6) and one can see that stagnant water and summer polder areas were lost completely with time because the main dike was positioned as close as possible towards the river.

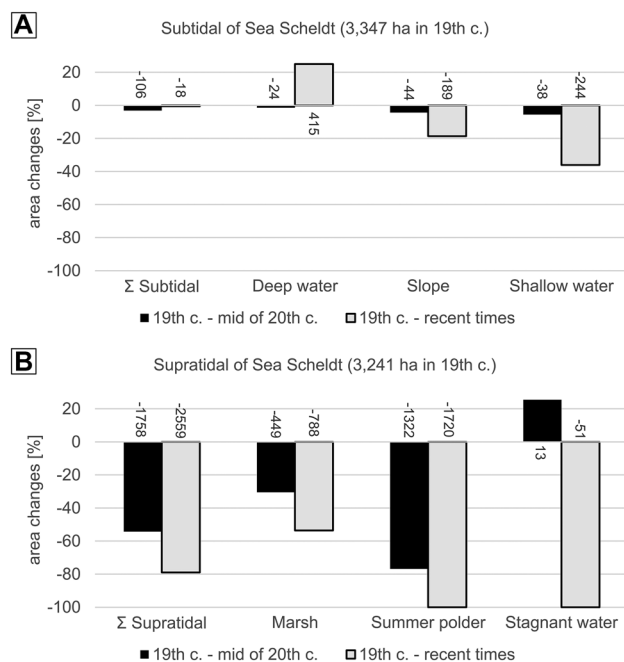


Fig. 6 Loss of supratidal (graph A) and subtidal (graph B) physiotope areas along the Sea Scheldt (%), calculated as difference of areas in nineteenth century. Minus area mid of twentieth century and minus recent areas

The extent of physiotope in the oligohaline zones showed the same trends (Fig. 4). The supratidal areas were affected by different hydraulic engineering such as straightening the fairways, protecting the foreland of dikes with summer dikes, land reclamation by new dikes, and higher tidal ranges upstream. Focusing on the supratidal, one can see that this occurred in the Elbe, the Weser, and the Sea Scheldt (Table 6), but mostly along the Sea Scheldt. Here, the supratidal areas were reduced by 78% from the nineteenth century to recent times. All supratidal physiotope areas were affected and summer polder and stagnant water areas were lost completely (Fig. 6).

5.2 Processes stimulating the observed spatial change of physiotope in an estuary

The geological substrate underlying an estuary can be seen as a starting point to form physiotope (Kusnierz and Sivers (2018)). Based on that, the hydrology can also influence the physiotope (Simon et al. 2017), because the velocity of currents determines which grain size of sediments is deposited or eroded (Hjulström 1935). Hence, engineering intervention altering the hydrology of estuarine systems will lead to changes in sedimentation and on the distribution of physiotope as well. Often higher currents were a favoured effect from a hydraulic engineer's perspective because the currents reduce sedimentation in the fairways (e.g. Franzius 1888). However, the elevated current velocity and tidal range increased the risk of flooding in upstream parts of the estuaries (e.g. Schuchardt et al. 2007). Consequently, upstream weirs were constructed and tributaries were cut off. The erosive power of the currents was controlled by groynes, training walls and shoreline structures. Again, these measures caused higher current velocities (Elsebach et al. 2007) and further penetration of the tides into the tidal river catchment (Fig. 1) (e.g. Meire et al. 2005; Fickert and Strotmann 2007; Schuchardt et al. 2007).

Of course, the question rises if this study can prove that a hydraulic engineering measure had influenced the physiotope patterns in an estuary. Solely based on our data, this is possible as far as the diking of supratidal areas is concerned. Interventions like straightening and deepening fairways, cutting of tributaries and installing weirs or groynes can change the hydrology in estuaries and hence the extent of physiotope on different time scales. However, Townend (2004) worked on such changes in estuaries and figured out that a response on engineering activities such as channelizing can be expected in a range of years up to decades. Consequently, it needs more than evaluating maps of two to three time points to prove and figure out the concrete effects of a single engineering measure on the distribution of physiotope.

Hence, our study could not identify the response of single hydraulic activity. Nevertheless, the study shows that

changes in the distribution of physiotypes can be registered after important engineering measures in the estuaries. Remarkably, we observed nearly no spatial change of physiotypes in the Humber. Here, the most impacting engineering activities had been implemented prior to the studied maps. In the other estuaries of Elbe, Sea Scheldt, and Weser the reference scenario was a baseline prior to the most important engineering measures with an impact on the hydrology. This difference between maps of the Humber and the other estuaries enhances the plausibility that the mentioned engineering

activities are the reason for the observed changes in the distribution of the physiotypes within the estuaries of the Elbe, the Sea Scheldt and the Weser.

To see the effects of a single engineering activity needs a dedicated monitoring programme and a more detailed look in time and space on a project scale. Examples of an appropriate scale are the investigation at Harriersand in the Weser estuary (Fig. 7) and the development of the Durme (Fig. 8), a tributary of the Sea Scheldt. Both are impressive cases showing the consequences of diking, straightening

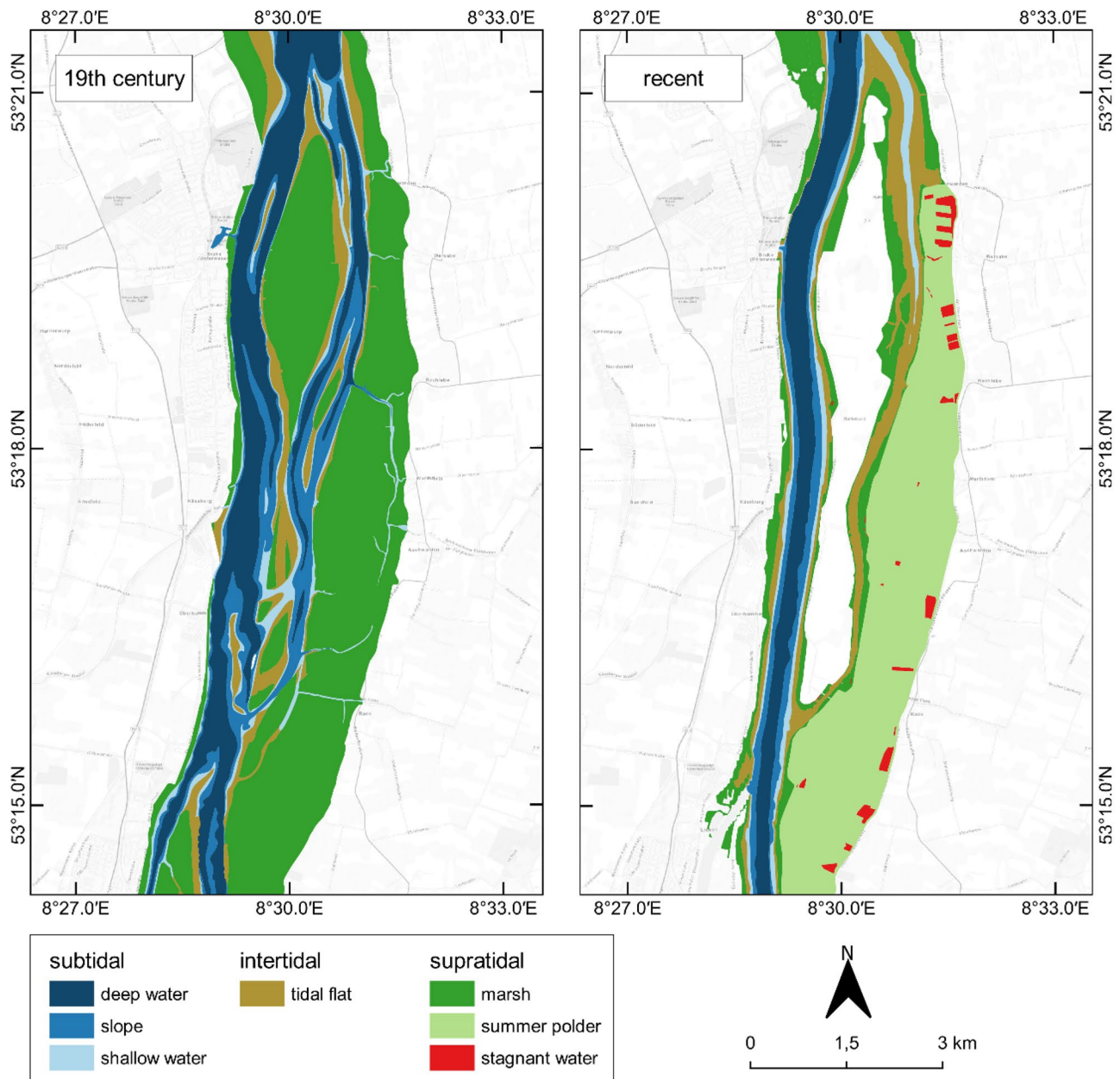


Fig. 7 The Weser at Harrier Sand in the nineteenth century and today (2008). In former days the river meandered in a wider river bed while now the water passes in a straightened deep canal. Broad parts of the

former river bed are sheltered with dikes or transformed into polders by summer dikes

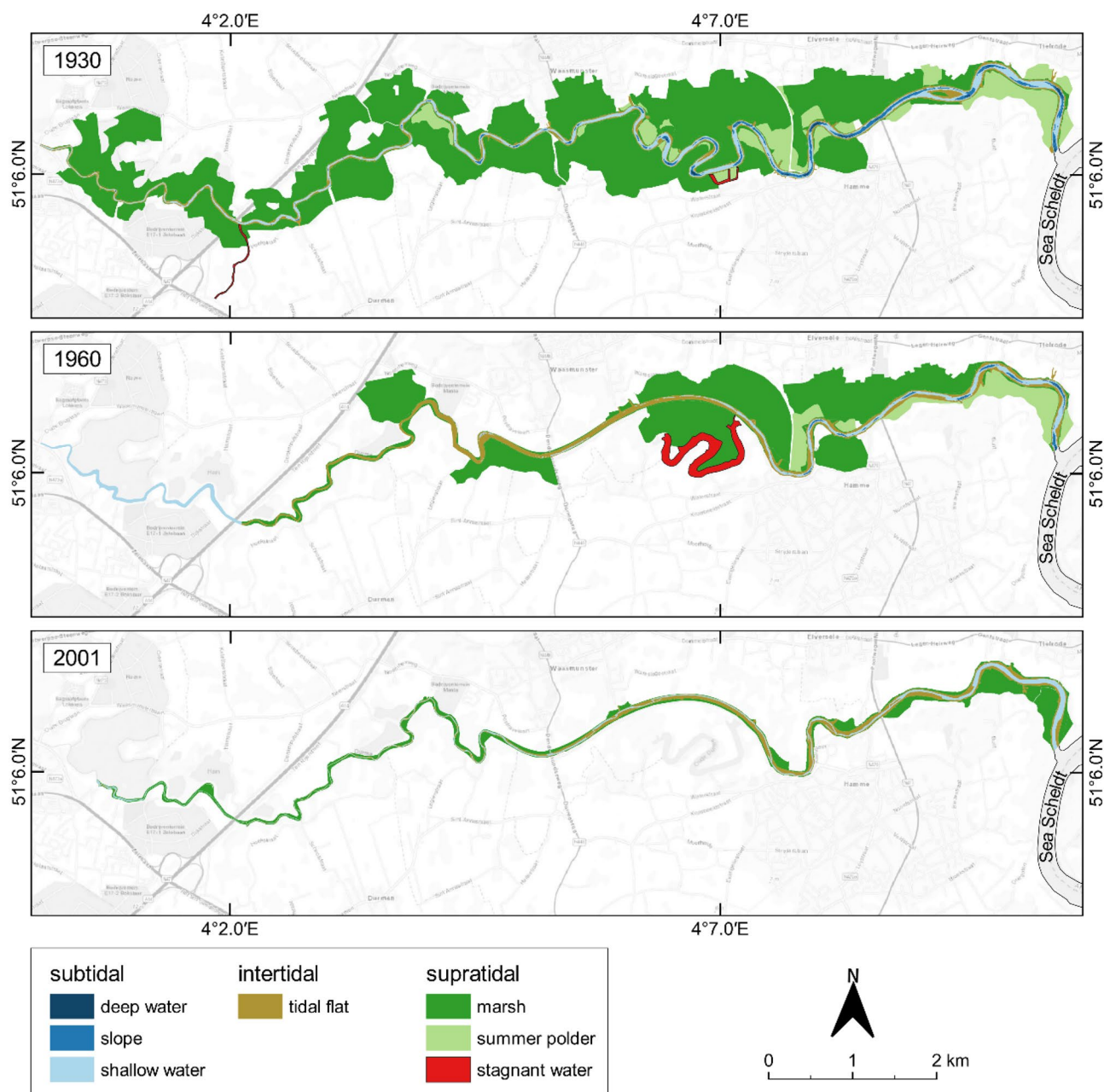


Fig. 8 The change of physiotopes along the Durme from 1930 to 2001 shows an impressive loss of areas, especially the summer polders and stagnant waters are affected

and deepening the main fairways on the extent of physiotopes. At Harriersand the originally braided fairways of the Weser were transformed into a single and deeper fairway by straightening and diking. Additionally, a former anabranch was enclosed by dikes and an island was created and protected with dikes (Fig. 7).

Looking at the Durme (Fig. 8), the effects of straightening and diking led to a significant loss of supratidal summer polder and stagnant waters until recent times. In both examples,

the loss of shallow water physiotopes was inevitably linked to hydraulic engineering projects.

6 Conclusions and outlook

This study exhibits the temporal changes of littoral physiotopes in estuaries at the North Sea. Our approach to map such physiotopes at different time steps since the end of the

nineteenth century allowed the quantification of their spatial alteration. As one important result, the collected data, maps and created shape files represent a comprehensive reference scenario for assessing the spatial effects of future management options or interventions in the Elbe, Humber, Sea Scheldt, and Weser estuaries.

Additionally, the consideration of salinity zones made obvious that most changes took place in the upstream parts of the estuaries in freshwater and oligohaline zones. Here the highest spatial loss along the estuaries was determined. This is a relevant aspect of this study because areas in each salinity zone host different biological communities. At the first glance, it may be logical to focus environmental management of estuaries on areas where the greatest spatial losses were calculated. However, such a spatial focus should consider the connectivity of habitats and potentially the continuum of ecosystems and their services along an estuarine system in particular.

For two reasons we consider this an important aspect, first, because the next generation of container vessels is pending, with a likely further increase in size. This raises the question if a further deepening of fairways still remains an appropriate management action given the loss of physiotope areas that might occur, and second, such losses might be compensated spatially, e.g. by creating new habitats in other places (e.g. Mander et al. 2007). However, this is a complicated task if the habitat connectivity, particularly between different salinity zones is to be maintained. Since a connectivity among different salinity zones is vital for a sustainable and resilient estuary (Elliott et al. 2019), it is recommended that the maintenance or enhancement of such connectivity is a priority for future management and compensatory interventions.

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Data availability An annex with details on maps and charts and GIS-shape files of physiotopes of all estuaries area is available as supplement and can be downloaded.

Declarations

Conflict of interest The authors declare not to have any conflict of interest.

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References

- ABPmer (2004) Historical analysis of Humber estuary morphology, report for environment agency, North East region, ABP Marine Environmental Research Ltd, Southampton, Report No: R.1005
- Atkins WS (2002) Warming up the region: the impacts of climate change in the Yorkshire and Humber region. WS Atkins report no: AK2970.068.dg.013, Epsom. pp 109
- Boyes S, Elliott M (2006) Organic matter and nutrient inputs to the Humber Estuary, England. *Mar Pollut Bull* 53:136–143
- Caspers H (1959) Vorschläge einer Brackwassernomenklatur: "the Venice system". *Int Rev Ges Hydrobiol* 44:313–315
- Cohen KM, Finney SC, Gibbard PL, Fan JX (2013) The ICS International Chronostratigraphic Chart. *Episodes* 36:199–204
- Davidson NC (2014) How much wetland has the world lost? Long-term and recent trends in global wetland area. *Mar Freshwater Res* 65:934–941. MF14173
- Decler K, Wouters J, Jacobs S, Staes J, Spanhove T, Meire P, Van Diggelen R (2016) Mapping wetland loss and restoration potential in Flanders (Belgium): an ecosystem service perspective. *Ecol Soc* 21(4):46. <https://doi.org/10.5751/ES-08964-210446>
- Dugan JE, Airolidi L, Chapman MG, Walker SJ, Schlacher T (2011) Estuarine and coastal structures: environmental effects, a focus on shore and nearshore structures. In: Wolanski E, McLusky D (eds) *Treatise on estuarine and coastal science*. Academic press, pp 17–41. <https://doi.org/10.1016/B978-0-12-374711-2.00802-0>. ISBN 9780080878850
- Elliott M, Day JW, Ramachandran R, Wolanski E (2019) Chapter 1 - a synthesis: what is the future for coasts, estuaries, deltas and other transitional habitats in 2050 and beyond?. In: Wolanski E, Day JW, Elliott M, Ramachandran R (eds) *Coasts and Estuaries*. Elsevier, pp 1–28. <https://doi.org/10.1016/C2017-0-00731-0>. ISBN 978-0-12-814003-1
- Elsebach J, Kaiser R, Niemeyer HD (2007) HARBASINS Report: spatial balance of habitats in the Weser Estuary. Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency

- Coastal Research Station. http://tide-project.eu/downloads/Spatial_Habitat_Development_Weser_Estuary.pdf. Accessed 16 Mar 2022
- Environment Agency (2011) The Humber Environment in Focus 2011. Environment agency, Leeds 59
- Farina A (1998) Principles and methods in landscape ecology. Chapman & Hall, London
- Fickert M, Strotmann T (2007) Hydrodynamische Entwicklung der Tideelbe. In: Gönner G, Pflüger B, Bremer JA (eds) Von der Geoarchäologie über die Küstendynamik zum Küstenzonenmanagement. Coastline Reports 9, pp 59–68. ISSN 0928–2734; ISBN 978–3–9811839–1–7
- Forman RTT (1995) Land mosaics. Cambridge University Press, Cambridge
- Franzius L (1888) Die Korrektur der Unterweser (Bremen, Nachdruck von 1991 mit ergänzenden Anmerkungen von Dipl.-Ing. Jan Dirksen). In: Die Küste 51 Sonderheft. Heide, Holstein: Boyens. S. 39–73.
- Freitag C, Hochfeld B, Ohle N (2007) Lebensraum Tideelbe. In: Gönner G, Pflüger B, Bremer JA (eds) Von der Geoarchäologie über die Küstendynamik zum Küstenzonenmanagement. Coastline Reports 9, pp. 69–79. ISSN 0928–2734; ISBN 978–3–9811839–1–7
- Geerts L, Wolfstein K, Jacobs S, van Damme S, Vandenbruwaene W (2012) Zonation of the TIDE estuaries. Internal TIDE report 19
- Hjulström F (1935) Studies of the morphological activity of rivers as illustrated by the River Fyris. In: bulletin of the Geological Institute University of Uppsala 25:221–227. Uppsala
- Kennish JM (2019) Practical Handbook of Marine Science. 4th ed. CRC Press, Taylor & Francis Group, Boca Raton, London, New York, 527
- Kerner M (2007) Effects of deepening the Elbe estuary on sediment regime and water quality. Estuar Coast Shelf Sci 75:492–500
- Kiden P, Denys L, Johnston P (2002) Late Quaternary sea-level change and isostatic and tectonic land movements along the Belgian-Dutch North Sea coast: geological data and model results. J Quaternary Sci 17(5–6):535–546
- Kusnierz PC, Sivers E (2018) How important is geology in evaluating stream habitat? J Soils Sediments 18:1176–1184. <https://doi.org/10.1007/s11368-017-1885-z>
- Lucker T, Busch D, Knötzel J, Schirmer M (1995) Unterweserausbau, Entwicklung des Schiffsverkehrs und Auswirkungen auf das Flusssystem. In Gerken B, Schirmer M (eds) Die Weser. Limnologie aktuell, 6:301–312
- Mander L, Cutts ND, Allen J, Maziket K (2007) Assessing the development of newly created habitat for wintering estuarine birds. Estuar Coast Shelf Sci 75:163–174. <https://doi.org/10.1016/j.ecss.2007.04.028>
- Meire P, Ysebaert T, Van Damme S, Van den Bergh E, Maris T, Struyf E (2005) The Scheldt estuary: a description of a changing ecosystem. Hydrobiologia 540:1–11
- Morris RKA, Mitchell SB (2013) Has loss of accommodation space in the humber estuary led to elevated suspended sediment concentrations? Int J Frontiers in Construction Eng 2(1):1–9
- Natuhara Y (2006) Landscape evaluation for ecosystem planning. Landsc Ecol Eng 2:3–11. <https://doi.org/10.1007/s11355-006-0033-5>
- Schuchardt B, Schirmer M (2005) Klimawandel und Küste. Die Zukunft der Unterweserregion. Springer-Verlag Berlin Heidelberg 341:p 81 fig. ISBN 3–540–43310–4
- Schuchardt B, Scholle J, Schulze S, Bildstein T (2007) Vergleichende Bewertung der ökologischen Situation der inneren Ästuarie von Eider, Elbe, Weser und Ems. In: Gönner G, Pflüger B, Bremer JA (eds) Von der Geoarchäologie über die Küstendynamik zum Küstenzonenmanagement. Coastline Reports 9, pp 15–25. ISSN 0928–2734; ISBN 978–3–9811839–1–7
- Simon MR, Zogg GP, Travis SE (2017) Impacts of sea-level rise on sediment microbial community structure and function in two New England salt marshes, USA. J Soils Sediments 17:2847–2855. <https://doi.org/10.1007/s11368-017-1710-8>
- Townend IH (2004) Identifying change in estuaries. J Coast Conservation 10:5–12
- Tran NK, Haasis HD (2015) An empirical study of fleet expansion and growth of shipsize in containerliner-shipping. Int J Prod Econ 159:241–253
- Van der Belt M, Costanza R (2011) Ecological economics of estuaries and coasts. Treatise on Estuarine & Coastal Science. Vol. 1 Elsevier, Amsterdam
- Vauclin S, Mourier B, Tena A, Piégay H, Winiarski T (2020) Effects of river infrastructures on the floodplain sedimentary environment in the Rhône River. J Soils Sediments 20:2697–2708. <https://doi.org/10.1007/s11368-019-02449-6>

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