# Intertidal landscape response time to dike breaching and stepwise re-embankment : A combined historical and geomorphological study

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## TITLE

# INTERTIDAL LANDSCAPE RESPONSE TIME TO DIKE BREACHING AND STEPWISE RE-EMBANKMENT: A COMBINED HISTORICAL AND GEOMORPHOLOGICAL STUDY

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**ABSTRACT**

Intertidal flats and marshes provide important ecosystem services to coastal and estuarine societies, and have therefore been subject to extensive research. Most of these studies, however, have one thing in common: intertidal landscape response has been studied from a rather short-term perspective, mostly less than 100 years. Furthermore, the impact of embankment practices on the development of the remaining intertidal area and its stability has hardly been studied at all. In this paper, a longer term perspective (sixteenth to twenty-first centuries) is used in order to (1) reconstruct intertidal landscape evolution, using both historical and soil maps, and (2) assess the effect of stepwise embankment on the intertidal area, both in terms of the surface proportions of the different components of an intertidal area and the vertical and lateral sediment elevation and sedimentation rates. The reconstruction and embankment effect assessment will be applied to the Land of Saeftinghe, an intertidal area in the Western Scheldt estuary that was partially re-embanked in a stepwise manner into an embankment landscape called the Waasland polder area (Belgium/The Netherlands). Important outcomes of this study are: (1) a combination of historical-geographical methods prove to be a valuable tool for past intertidal landscape reconstruction; (2) dike breaching and partial (stepwise) re-embankment are important driving mechanisms for the evolution of the remaining intertidal landscape towards new equilibrium conditions, though the new landscape equilibria can only be reached with a certain time lag; (3) subsequent embankments with a short time interval (15 to 21 years) prevent tidal marsh surface areas from reaching an equilibrium state; and (4) between 60 to 96 years are needed for tidal marsh elevation to reach an equilibrium.

**KEYWORDS (6)**

Intertidal landscape response, embankment practices, historical maps, equilibrium state, sediment elevation, sedimentation rate

**ABBREVIATIONS**

*Agentschap Geografische Informatie Vlaanderen = AGIV*. Historical archives, abbreviated in the text or tables: *ARA = Algemeen Rijsarchief; RAG = Rijksarchief Gent; ZA = Zeeuws Archief Middelburg; NADH = Nationaal Archief Den Haag.*

## 1. INTRODUCTION

Intertidal areas (in this case defined as tidally influenced areas existing in between mean high-water level at spring and neap tides, MHWS and MHWN respectively) along coastal embayments and estuaries typically consist of: (1) tidal channels, located below mean low water level (MLWL), flooded permanently except during neap tide; (2) tidal flats, the unvegetated area in between MLWL and mean high water level (MHWL); and (3) tidal salt or brackish marshes (for conciseness further called 'tidal marsh' in the rest of this paper), the vegetated area above MHWL, only flooded during spring tide (Temmerman et al., 2013). As tidal flats and tidal marshes provide important ecosystem services to coastal and estuarine societies. This includes, for example, protection against the impact of storms (e.g. Temmerman et al., 2013) and the provision of nursery grounds for fish (e.g. Barbier et al., 2010). The processes that shape these intertidal landscapes have been subject to extensive research, which has often focused on sedimentation processes and the role and development of tidal channels as the main supplier of sediments within the system (Stumpf, 1983; Zeff, 1988; Ichoku and Chorowicz, 1994; Eisma, 1998; Middelkoop and Asselman, 1998; Allen, 2000; Novakowski et al., 2004; Temmerman et al., 2004b; D'Alpaos et al., 2005; French, 2006; D'Alpaos et al., 2007). Most of these studies, however, have one thing in common: intertidal landscape response has been studied from a rather short-term perspective, mostly less than 100 years.

In many estuaries in the world, intertidal areas occurring naturally along estuaries, have often been reclaimed on a large scale by the building of dikes (Rippon, 2000). To avoid terminology issues, in the rest of this article the term ‘dike’ is used for a man-made sea wall that prevents tidal flooding. Of course, during successive embankments former sea dikes can be changed to inner dikes, only separating embankments, since new dikes were built further seaward. Examples of large scale reclamations are found in, for instance, the Elbe Estuary, Schleswig Holstein, Germany/Denmark (Hoffmann, 2004; Meier, 2013) or the Fenlands/Thames estuary in the United Kingdom (Rippon, 2000; Galloway, 2009). These embankments have mostly occurred stepwise. Such stepwise embankment of an intertidal area may be expected to trigger a geomorphological response of the remaining intertidal area in front of the newly constructed dike. However, the exact consequences of these practices on the morphology of the intertidal area have, apart from a few cases (Hood, 2004; Cuvilliez et al., 2009; Dias and Picado, 2011), not been studied intensively. The focus has mostly been on intertidal landscape response to natural forcing factors, such as a rise in sea level, the impact of storms, etc., while much less attention has been paid to the interaction with social processes such as embankment practices. The opposite process also takes place: in many estuaries dike breaching and de-embankment or so-called managed coastal realignment for purposes of nature restoration or coastal defense are recent practices. This has triggered some research on intertidal landscape evolution in de-embanked areas (see for instance: Vandenbruwaene et al., 2012), however, these studies are only available for short periods of landscape evolution (a few years to a few decades).

This does not mean that efforts on past (coastal) landscape reconstructions have not been made. Studies covering a time scale of the past 100 years have made use of aerial photographs (Martinez et al., 2011; Vandenbruwaene et al., 2013), recent historical maps (Zawiejska and Wyzga, 2010) or a combination of both techniques (Timár et al., 2008). Otherwise, landscape reconstructions for a time-scale greater than 100 years, solely based on historical maps, have also been attempted, both in coastal (de Boer and Carr, 1969; Lloyd and Gilmartin, 1987; Burningham, 2008; Maio et al., 2013) and in non-coastal areas (Stankoviansky, 2003; Uribelarrea et al., 2003; Bender et al., 2005). However, to the best of our knowledge and with exception of the works of Burningham and French (2006) and Burnigham (2008) who analyzed time periods of ca. 200 years, a long-term (> 100 or > 200 years) comprehensive reconstruction of an intertidal area (based on historical maps) with a level of detail that distinguishes tidal channels, tidal flats and tidal marshes, does not exist. It is precisely this level of detail which is needed in order to assess the long-term interactions between (de-)embanking and intertidal area evolution.

Present-day soil structure can prove a valuable addition to the information gained from historical maps. General intertidal area development theories point to a declining sediment particle size with increasing distance from the source of sediment (in this case the tidal channels) towards the landward side of the intertidal area, at least in tide-dominated systems (Luternauer et al., 1995; Eisma, 1998; Woodroffe, 2003; Temmerman et al., 2004a). This trend has been (partly) verified by separate case-studies (Stumpf, 1983; Flemming and Ziegler, 1995; Shi et al., 1995; Yang et al., 2008; Wang et al., 2013). However, the interaction between former intertidal area and grain size patterns in reclaimed (or enclosed) areas (which are displayed on present-day soil maps) has, with some exceptions (Allen, 1992; Allen and Haslett, 2006; Clarke et al., 2014), hardly been studied yet.

Besides intertidal area structure and sedimentation processes, the equilibrium (or stability) of tidal marshes has been investigated extensively. This stability of an intertidal area is nowadays regarded as a system with multiple stable states, which can shift in between different states when a critical threshold is reached (Fagherazzi et al., 2006; Marani et al., 2010; Wang and Temmerman, 2013). Here we distinguish between the stability of two components of the tidal marsh landscape, i.e. the vertical elevation of the tidal marsh platform (relative to mean sea level) and the lateral extent (size or area) of the tidal marsh. Regarding stability in terms of vertical elevation of the tidal marsh, it is accepted that a bimodal distribution of elevation is present (Fagherazzi et al., 2006; Wang and Temmerman, 2013): as a consequence of feedbacks with vertical sedimentation and erosion processes, intermediate elevations tend to either erode to lower-lying bare tidal flats, located below MHWL, or to accrete towards higher-lying vegetated tidal marshes, above or close to MHWL (Defina et al., 2007; McGlathery et al., 2013; Wang and Temmerman, 2013). Previous research has revealed that vertical growth is, theoretically characterised by an asymptotic growth curve with a rapid rise in the first period of tidal marsh formation, followed by very slow rates when the tidal marsh starts to reach MHWL-elevation (Pethick, 1981; Allen, 1990; French, 1993; Temmerman et al., 2004b). As soon as the tidal marsh platform has reached this equilibrium level close to MHWL, vertical sediment accretion will take place, in theory, at a similar rate as the rate of mean sea level or MHWL rise (Temmerman et al., 2004b; Kirwan et al., 2010;

Fagherazzi et al., 2012). Note that the accumulation to this close to MHWL-equilibrium level requires there is sufficient suspended sediment available (Kirwan et al., 2010). The equilibrium state of the lateral extent or surface proportion of tidal marshes, flats and channels within a given intertidal area, has been studied much less extensively. This surface proportion of tidal marshes and flats seems to differ depending on local circumstances, which sometimes leads to an equilibrium consisting of mainly tidal flats (Fagherazzi et al., 2006), and sometimes mainly of tidal marsh (e.g. as observed in the present-day Saeftinghe tidal marshes in the Scheldt estuary (Wang and Temmerman, 2013)).

Given the current state of research, as described above, it is clear that general intertidal processes are studied widely, but not commonly on timescales over 100 years. Furthermore, responses to anthropogenic factors (such as re-embankment) have gained far less attention than ecological interactions. Here, as a test-case, we examine the long-term (> 400 years), socio-ecological interactions which have shaped the Waasland polder area (see section 2) and its adjacent tidal marsh, the Land of Saeftinghe. This area is situated along the estuary of the river Scheldt, on both sides of the present-day boundary between Belgium and the Netherlands. After catastrophic inundations at the end of the sixteenth century, part of the area was re-embanked and turned into 'polders' for mainly agricultural land-use.

Our first objective is to reconstruct the intertidal landscape and its evolution (i.e. the location of tidal channels, tidal flats and tidal marshes) over the last ca. 400 years in an intertidal area that has been de-embanked and re-embanked over this period, in a stepwise manner. The extent to which this landscape reconstruction can be done by using a combination of historical maps and analysis of present-day soil texture patterns in the re-embanked areas will be investigated. The results are therefore important both for understanding long-term, socio-ecological interactions within estuaries, as well as on a more methodological level since the developed method could be also applied in (comparable) future research.

The second objective of this paper is to assess the effect of stepwise embankment on the intertidal area. This will be done by (1) surface analysis on the percentages of tidal marsh, tidal flat and tidal channels, based on the GIS-reconstructions, and (2) assessment of the response of the lateral and vertical tidal marsh accretion rates in front of the embankments. The time scales at which the lateral extent and vertical elevations of tidal marshes can reach an equilibrium condition in response to the construction of embankments will also be investigated.

## 2. REGIONAL SETTING

The study area is located along the (Western) Scheldt estuary, on the present-day border of The Netherlands and Belgium (Fig. 1). It consists of the Belgian Waasland polder area, the Dutch polders north of the border, and the adjacent brackish intertidal area (Land of) Saeftinghe. The studied time frame begins during the late Middle Ages (the end of the sixteenth century) and stretches across the Early Modern period until the twenty-first century. In the following, a short palaeogeographical overview of relevant Quarternary (pre-medieval) evolution in the study area, and the (Western) Scheldt estuary is given.

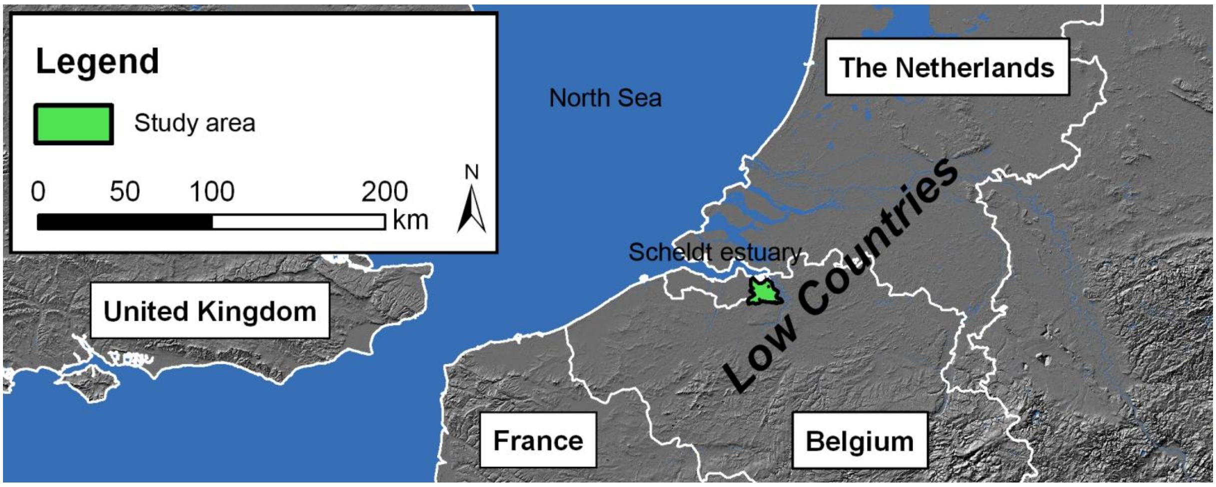


Fig. 1: Study area and its surroundings. [black-and-white in press, color version provided for web only]

The study area is characterized by Late Glacial and Holocene deposits which lie directly on top of Tertiary formations (Formation of Lillo, Kattendijk and Boom (Jacobs et al., 1993; 2010a; b)). Due to the cold and windy climate which existed during the Late Glacial period, sand dunes were formed on the coastal plain of present-day Belgium. One of the largest was the sand-ridge Maldegem-Stekene (Verbruggen et al., 1991), of which the furthermost eastern parts stretched out into the area of study. During the Early Holocene period the sea level rose rapidly, however, tidal activity in the southern Netherlands was limited leading to the development of a shallow, brackish, lagoonal environment. Around 6500 cal. yr BP, when the sea reached its furthest inland position, peatland formation started in the coastal wetlands surrounding the North Sea (Vos and van Heeringen, 1997). Since the period of rapidly rising sea level came to an end, coastal barrier islands were able to develop. This created favourable conditions for peat growth behind such barriers and a large peat layer developed which, by 3500 BP, covered the entire area of the (present-day) southwestern Netherlands and parts of northwestern Belgium, including most of the study area. The end of this coastal peat growth appears to have been highly variable from place to place (Baeteman and Declercq, 2002;

Long et al., 2006; Baeteman, 2008). In the Waasland polder area peat growth possibly continued up to 600 AD (Heirman et al., 2013). By then the study area consisted of extensive peat lands, intersected by the eastern ends of the sand ridge of Maldegem-Stekene (Augustyn, 1977). During this period the river Scheldt did not flow into the North Sea through the Western Scheldt, but northward through the present-day Eastern Scheldt. Between 800 and 1000 AD the *Honte* (predecessor of the Western Scheldt), a small sea arm stretching from the North Sea in an eastward, or landward, direction became connected to the Eastern Scheldt (Vos and van Heeringen, 1997). For centuries after this, the Eastern Scheldt still remained the main outlet of the river Scheldt to the sea. However, due to increasing embankment activity (resulting in higher water levels) and the subsequent large-scale flooding in the fourteenth/fifteenth centuries (late medieval period), the Western Scheldt became the main outlet whereas the Eastern Scheldt slowly silted up (Coen, 2008; Soens, 2013). Sea-level and tidal prism in the Western Scheldt have shown a gradual rise ever since (van der Spek, 1997). Nowadays, the tidal range varies from 4.46 m (spring tide) and 2.97 m (neap tide) at the mouth of the estuary, over a maximum of, respectively, 5.93 and 4.49 m further inland (Rupelmonde), to a minimum of 2.24 and 1.84 m in Ghent (Temmerman et al., 2003).

## 3. MATERIAL AND METHODS

### 3.1 Use of historical maps for intertidal area GIS-reconstructions

For this part of the paper, our aim is to present five reconstructions of the past intertidal landscape. These time sections represent (1) the maximal extension of medieval land reclamations (around 1570 AD); (2) the results of the catastrophic inundations (around 1600) and (3-5) the situation just after major re-embankment works (approximately 1700, 1790 and

1850 AD). A selection of historical maps was made for these five time sections. A large GIS-database was first created with approximately 300 (roughly) geo-referenced and chronologically ordered historical maps, dating from the sixteenth to the twentieth century. Three criteria were then used to select the definitive maps (see Appendix) for the reconstruction. Firstly, the date displayed on the map (which can differ from the manufacturing date of older maps) should be close to the pre-defined time sections. Secondly, sufficient topographical details (differentiation between tidal channels, tidal flats and tidal marsh) should be depicted. Thirdly, the map with the lowest Mean Positional Error (MPE, see also Jongepier et al. (2014, forthcoming)) should be selected where multiple suitable maps exist. The MPE should be interpreted as the average distance between a randomly chosen point on the historical map (after translation, rotation, and scaling) and its actual position. The lower the MPE, the more geometrically accurate the historical map. MPE was calculated using specialist software *MapAnalyst* (Jenny, 2006; Jenny et al., 2007; Jenny and Hurni, 2011) but could also be done by simply using *ArcGIS* or *QuantumGIS.* A qualitative interpretation, however, remains unavoidable (Fig. 2). Based on this selection of maps, dates of the reconstructions were refined to 1570, 1625, 1700, 1791, 1852 AD.


**(a)** **(b)**

Fig. 2: Qualitative interpretation during the selection of maps. (a) Map from 1791 AD (ZA, Aanwinsten, n° 41) with a MPE of 104 meters. (b) Map from 1816 AD (ARA, Kaarten & plans, n° 8554) with a MPE of 32 meters. Usually, map (b) which has a lower MPE is preferred. For this particular time frame, which includes a date aiming to be in 1790 AD, the map with the closest manufacturing date (1791 AD) was selected. [black-and-white in press, color version provided for web only]

Ground Control Points were used by *ArcGIS* to reposition the historical map to its present day location, as given by topographical maps (Nationaal Geografisch Instituut, scale 1:10.000). For digitizing purposes, the ‘spline transformation’ was used, which produces a perfect overlap of the Ground Control Points. For each time frame, a *polygon layer* was created and the features, as given by the historical maps, were digitized, making a distinction between embanked and unembanked land. Within the unembanked zone, further distinctions were made between tidal channels, tidal flats, tidal marshes and undrained land (located above MHWS). Embankments (in this paper defined as drained areas, enclosed by dikes) were in most cases retraced to the present-day situation, making their reconstructed limitations perfectly overlapping with the current limitations. Data regarding Mean Positional Errors, displayed dates, map references and complementary information was stored in *attribute tables*. Furthermore, for each individual polygon, the present-day area was calculated in km². In section 3.3 we explain in more detail how the reconstructed landscape evolution was analysed in terms of time scales of intertidal landscape response to stepwise embankments.

### 3.2 Use of soil texture patterns for intertidal landscape reconstruction

As historical maps do come with their limitations concerning accuracy (Jongepier et al., 2014, forthcoming), additional sources of information should be applied when undertaking landscape reconstruction. In this part of the paper, we assess to what extent present-day soil archives (in this particular case provided by the Belgian soil charts) can be used as source of information. In order to do so, it is important to find out what correlation exists between soil structure in later embankments and the former intertidal area. Therefore, grain size distributions of both the remaining intertidal area and the re-embanked area were compared. We base ourselves on the hypothesis for grain size distribution similarities in embankments and the corresponding former intertidal areas, as given in Fig. 3.

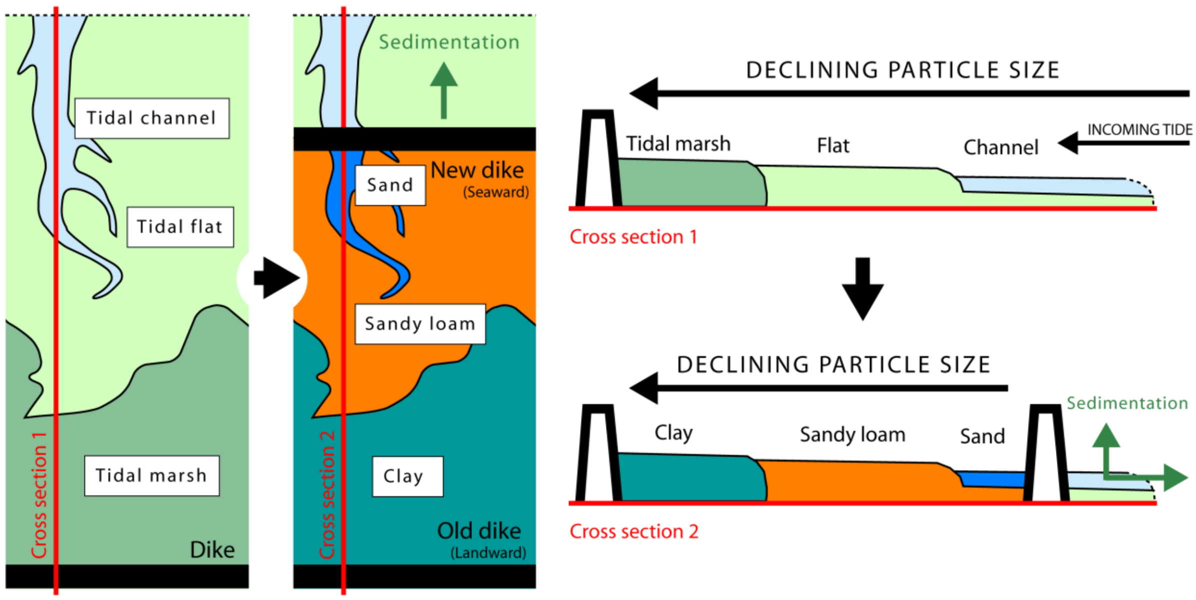


Fig. 3: Hypothesis for grain size distribution similarities in embankments and the corresponding former intertidal areas. [black-and-white in press, color version provided for web only]

An intertidal area is, in general, characterized by declining particle size from the seaward to the landward side (Luternauer et al., 1995; Eisma, 1998; Woodroffe, 2003; Temmerman et al., 2004a). This general theory (for more refined information, see for instance Rahman and Plater , 2014) implies that coarse material (sand) is deposited in the tidal channels, while the finest sediments (clay) are found on the tidal marshes. In the tidal flats silt (or sandy loam, according to the Belgian soil classification) was deposited. One might hypothesise that this typical intertidal grain size pattern is 'fossilized' when the area is embanked, leading to a repeating series of soil sequences if subsequent embankments were undertaken. The former tidal flat, which extended further seaward at the time the new dikes were constructed, would then be found at the base of the next sedimentation layer adjacent to the dike, which would consist of a tidal marsh with clay particles. The inner dike soil sequence could therefore be used to approximately reconstruct the former intertidal structure. Note that this hypothesis assumes a part of the more seaward tidal flat was also comprised in the embankment. This is definitely the case for the embankments we analyze in detail (see below), but in some other cases only the higher elevated tidal marsh was embanked. However, in these cases the dikes were usually built at the most outer border of the tidal marsh, meaning only a small strip of tidal marsh would be left on the seaward side, directly followed by tidal flats and tidal channel, and the sedimentation process would also be re-initiated directly seaward of the new dike. In our specific test-case this re-initiation is apparent on the GIS-reconstructions, which we will discuss in section 4.1, in the form of newly formed tidal marshes outside new embankments. Profound impacts of 'coastal squeeze' (French, 2001), leading to loss of tidal marsh, are therefore absent.

In order to test our hypothesis (Fig. 3), soil samples were taken in three areas dating from the seventeenth to nineteenth centuries which were previously part of the intertidal area (*Land of Saeftinghe*)*: Oud-Arenbergpolder (finished in 1688 AD), Nieuw-Arenbergpolder (1784 AD)* and *Prosperpolder (1846 AD).* For each of the three embankments, ten soil samples were taken in three soil type zones that were deduced from the Belgian soil map (Digitale bodemkaart van het Vlaams Gewest, 1/20.000, AGIV, 2001): clay zones, sandy loam and sand, respectively, amounting to 90 soil samples in total (Fig. 4). On the Belgian soil maps, soils are classified according to a three-class formula, containing information on soil type, drainage class and separate soil layers. The digitalized version contains a legend which takes soil type and drainage class into account (Ameryckx, 1974). For this analysis, we simplified this to a legend containing soil type only.

For comparison, in the present-day remaining intertidal area (*Land of Saeftinghe)* ten samples were taken in tidal marsh (to be compared to clay), tidal flat (to be compared to sandy loam), tidal channels in marsh, tidal channels in flat and natural levees (adjacent to tidal channels, the latter three to be compared to sandy soils), amounting to fifty samples in total. Soil samples were collected using an Edelmann soil sampler for the top 20 cm of the surface.

The soil samples were mixed after which very coarse material was sieved out. Afterwards, a small amount (about 10 cc) of each sample was treated with $H_2O_2$ and *HCl* in order to remove organic material and carbonates. After about ten hours of treatment, the residue was heated to remove the remaining particles of organic material. The remaining soil sample was finely sieved (mesh size 1 mm), suspended in water and analyzed with the *Mastersizer S. (MALVERN)*, which reported grain-size distribution in eleven classes.

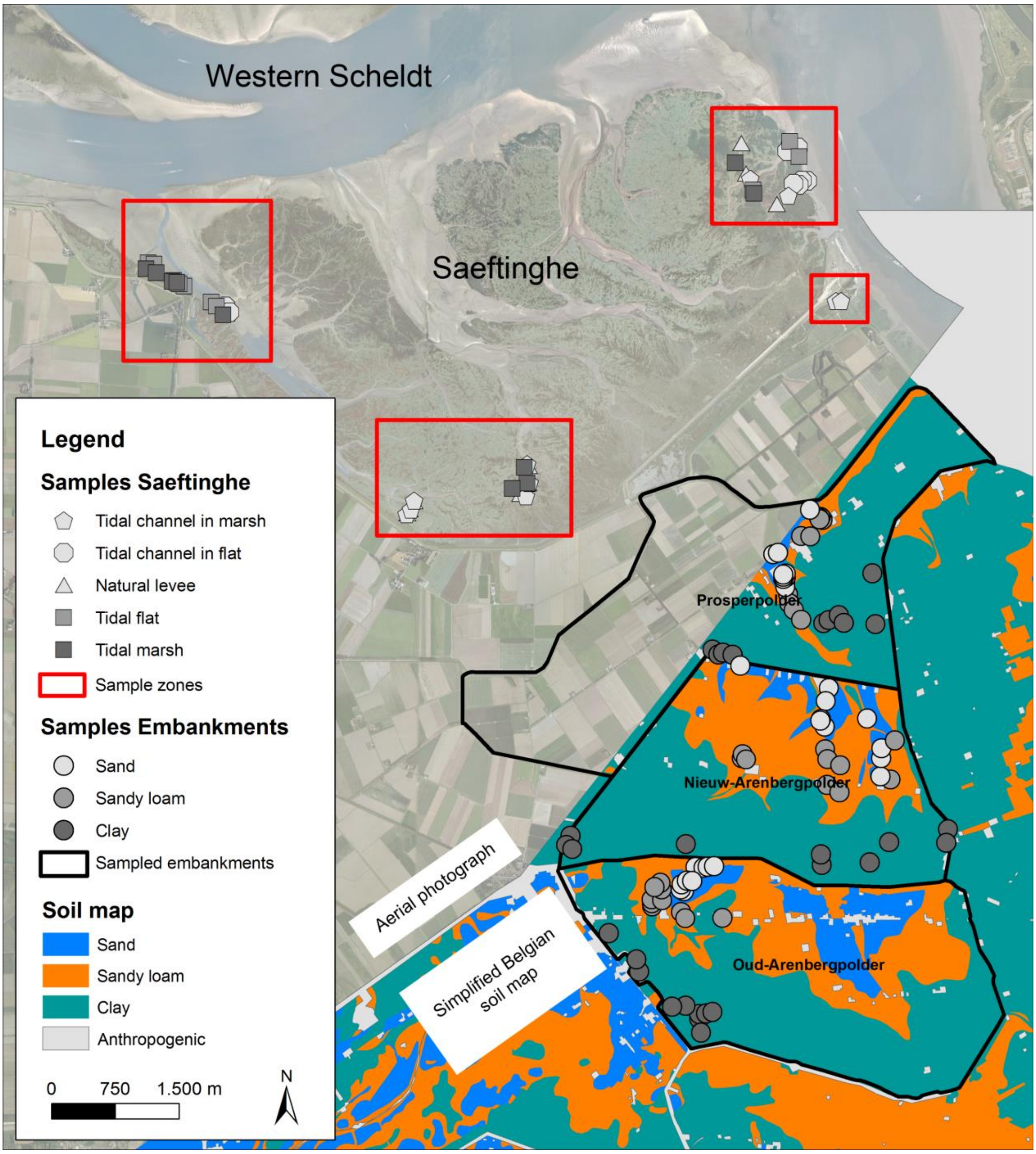


Fig. 4: Soil samples, taken from the embankments (classified according to location on the Belgian soil map) and Saeftinghe (classified according to location within the intertidal area). Background: aerial photographs and simplified Belgian soil map. ***[black-and-white in press, color version provided for web only]***

The output of the grain size analysis was classified to the Udden-Wentworth scale in order to obtain the clay fraction (<4 µm), silt fraction (4-63 µm) and sand fraction (>63 µm). These three fractions were plotted in a ternary diagram, according to percentages of clay, silt and sand. Furthermore, boxplots for each of the eight classes of sampling locations were made, according to the percentages of clay, silt and sand, in order to allow visual comparison of the characteristics of the embankment samples versus the tidal marsh samples. Statistical tests of the significant difference ($p<0.05$) between the means of the percentages of clay, silt and sand for the eight sample location classes were conducted using SPSS. For analysis where tidal marsh samples (sample size per class= 10) were involved, non-parametric Mann-Whitney tests were conducted. For the mutual comparison of the means of embankment samples (sample size per class = 30), ANOVA-tests were applied.

## 3.3 Assessment of the effects of the stepwise stepwise embankment on the intertidal area

### *3.3.1 Calculation of surface area percentages of tidal marshes, tidal flats and tidal channels*

Based on the GIS-layers, the total surface area of tidal channels, tidal flats and tidal marshes were calculated for each of the time steps (1570 AD, 1625 AD, 1700 AD, 1791 AD, 1852 AD). The area used for the calculations (indicated as “System Saeftinghe” in the maps) is limited by the extent of tidal marshes/flats (and the shortest cross-section of tidal channels possible) in the north. The southern limit is found in the maximum size of the tidal marsh as recorded in 1625 AD. These were compared to existing reconstructions of the intertidal landscape evolution in the twentieth and early twenty-first century (1931 AD, 1963 AD, 1992 AD, 2004 AD; published in Wang and Temmerman (2013)). These more recent reconstructions were derived from detailed historical topographic surveys (processed into DEMs – Digital Elevation Models) and historical aerial pictures (classified into bare tidal flats and vegetated tidal marshes) (Wang and Temmerman, 2013). Comparison of pre-1900 AD and post-1900 AD data was made due to the fact that the stepwise embankment of the intertidal area was stopped in the early twentieth century (the last embankment occurred in 1907 AD and the twentieth to twenty-first century data show the evolution of the remaining non-embanked intertidal area from a non-stable state (1931 AD) towards a stable state (1963 AD, 1992 AD, 2004 AD). Wang and Temmerman (2013) conclude that the system evolved towards a stable state because both the tidal marsh surface area (relative to the total remaining intertidal area) and tidal marsh elevation (relative to MHWL) showed significant changes between 1931 AD and 1963 AD. However, the changes in the tidal marsh area and elevation were strongly reduced and became very small towards 2004 AD (Fig. 5). Therefore, we consider the twentieth to twenty-first century data as a reference for landscape evolution towards an equilibrium state, which we then compare with our sixteenth to nineteenth century data, in order to assess the time scales of the landscape response to stepwise embankment of the intertidal area during the sixteenth to nineteenth centuries.

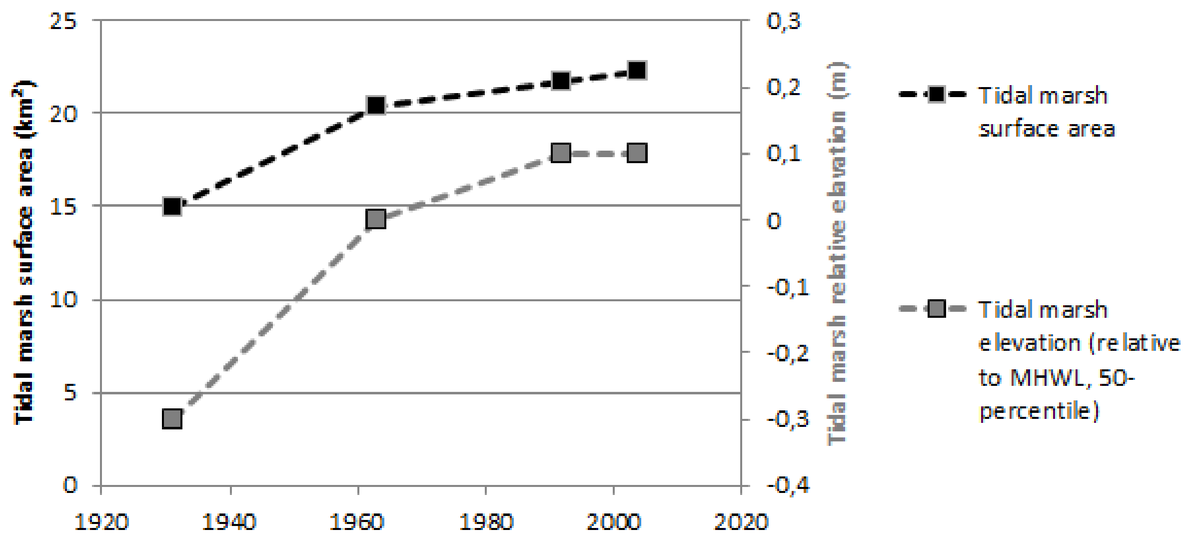


Fig. 5: Evolution towards an equilibrium state for both tidal marsh surface area and tidal marsh elevation (Land of Saeftinghe, based on Wang and Temmerman (2013).

### *3.3.2 Response of the lateral and vertical tidal marsh accretion rates in front of the embankments*

Several sediment elevations and elevation changes (further called sedimentation rates) were determined for the intertidal area *(Land of Saeftinghe),* both before and after 1900 AD (see below). Measured sediment elevation and sedimentation rates were compared to theoretical equilibrium sediment elevations and sedimentation rates before and after 1900 AD. With these theoretical Fig.s we point to the expected elevation and rate for a system that was in an equilibrium state. In addition, horizontal (lateral) yearly growth of the tidal marsh before 1900 AD was calculated. The basis of all the sediment elevations mentioned below is found in our hypothesis: when dealing with successive embankments, the former tidal flat was located at the landward side of any given dike. Sedimentation took place at the seaward side of this dike. Directly against the dike, a tidal marsh was formed, while the new tidal flats were located more seaward. When the next embankment was constructed, this sedimentation process stopped, but a new tidal marsh was formed on the seaward side of this new (sea) dike. Measuring or calculating the elevation of the former tidal marsh area seaward of the old dike and deducting the elevation of the area on the landward side of the dike gives the sediment elevation. For the more recent embankment, similar calculations for sediment elevation can be made measuring the elevation difference of the newer tidal marsh and the next area of tidal flats. By dividing these sediment elevations by the time elapsed between two successive embankments, the sedimentation rate can be calculated.

#### *3.3.2.1 Measured sediment elevation and sedimentation rate before 1900 AD ($Dh_{<1900}$ and $Dh_{<1900}/Dt_{<1900}$) and after 1900 AD in the Land of Saeftinghe ($Dh_{>1900}$ and $Dh_{>1900}/Dt_{>1900}$)*

Measured sediment elevation and sedimentation rate before 1900 AD ($Dh_{<1900}$ and $Dh_{<1900}/Dt_{<1900}$) was defined for three successive embankments: the *Oud-Arenbergpolder* (embankment completed in 1688 AD, located seaward of the *Kallo- and Konings-Kieldrechtpolders* of 1653/1654 AD), *Nieuw-Arenbergpolder* (embankment completed in 1784 AD, seaward of the *Oud-Arenbergpolder*) and *Prosperpolder* (embankment completed in 1846, AD seaward of the *Nieuw-Arenbergpolder*). This was done according to formulae 1 and 2*:*

$$Dh_{<1900} = (DB_{clay}/DB_{marsh}) * (H_{marsh} - H_{flat}) \quad (1)$$

*$DB_{clay}$ : Measured Dry Bulk density of the younger tidal marsh of Saeftinghe*

*$DB_{marsh}$ : Measured Dry Bulk density of the present- day clay area of the Oud-Arenbergpolder*

*$H_{marsh}$ : Measured present-day elevation in former tidal marsh zone new embankment (seaward of dike)*

*$H_{flat}$ : Measured present-day elevation in former tidal flat zone old embankment (landward of dike)*

$$Dt_{<1900} = T_{new} - T_{old} \quad (2)$$

*$T_{new}$ : Date of completion newer embankment (seaward)*

*$T_{old}$ : Date of completion previous embankment (landward)*

Elevations *($H_{marsh}$ and $H_{flat}$ )* were derived from the present-day Digital Elevation Model (DHM Vlaanderen, based on 5-m resolution LiDAR data, AGIV, 2001-2004). This was done in the following way: seaward and landward of the dikes of the successive embankments, zones corresponding to the minimal width of former tidal marsh/tidal flat (estimated using the soil maps, respectively clay and sandy loam zones) were digitized using ArcGIS 9.3. Large man-made features (such as major ditches or roads) were left out of these zones. Within these zones the average present-day elevation was calculated. *Dt* is actually the time period over which the tidal marsh was formed, starting from a tidal flat. This time period *Dt* is quantified as the period between a previous embankment (which triggered the formation of a tidal marsh on the tidal flat in front of the newly constructed dike) and a newer embankment of the tidal marsh in question. Sedimentation rates were simply calculated as *Dh/Dt*. Since the measured sediment elevation is an underestimation of the real sediment elevation (the soil was compacted during the centuries after embankment), a compensation factor based on (dry) bulk densities (DB, defined as the mass of oven-dried soil per original volume unit) was introduced. The DB for a tidal marsh (in this case) is more than two times smaller than the DB for a clay area since the tidal marsh originally contained a large amount of water (and probably also a significant portion of organic matter). This indicates that the original elevation of the tidal marsh (compared to the reference level) was more than two times higher than calculated without this compensation factor.

The other sediment elevations and sedimentation rates were derived using a combination of historical MHWL data derived from van der Spek (1997) and MHWL/elevation data from Wang and Temmerman (2013). MHWL is commonly defined relative to NAP *(Nieuw Amsterdams Peil)*, which is the Dutch reference level for elevation data. This level is close to the present-day mean sea level for the Dutch coast. Information on MHWL of the Scheldt estuary for 1650, 1800 and 1968 AD was provided by van der Spek (1997), while MHWL for 1931,1963,1992 and 2004 AD was provided by Wang and Temmerman (2013). MHWL for the specific embankment dates of 1653/1654, 1688, 1784 and 1846 AD was calculated through interpolation of the data for 1650, 1800 and 1986 AD. MHWL of 1902 was calculated through a combination of both (calculated) 1846 MHWL and 1931 MHWL (Table 1). Typical elevations, relative to MHWL, are given by Wang and Temmerman (2013). From their data, 20-, 50- and 80-percentiles for the typical elevation of tidal marshes and tidal flats were calculated (Table 2). These are the values for which respectively 20, 50 and 80% of the elevation observations in the total group of observations fall below.

Table 1: Mean High Water Levels, used for the sedimentation elevation and sedimentation rate analysis.

| **DATE** | **1653/54** | **1688** | **1784** | **1846** | **1902** | **1931** | **1963** | **1992** | **2004** |
|---|---|---|---|---|---|---|---|---|---|
| **MHWL (+m NAP)** | 1.27 | 1.40 | 1.74 | 2.10 | 2.27 | 2.36 | 2.53 | 2.70 | 2.76 |

Table 2: Elevation of the intertidal area, relative to MHWL (m)(derived from Wang and Temmerman, 2013)

| **PERCENTILES** | **1931** | **1963** | **1992** | **2004** |
|---|---|---|---|---|
| **Tidal marsh 20-percentile** | -0.8 | -0.3 | -0.1 | -0.2 |
| **Tidal marsh 50-percentile** | -0.3 | 0 | 0.1 | 0.1 |
| **Tidal marsh 80-percentile** | 0.1 | 0.1 | 0.2 | 0.3 |
| **Tidal flat 20-percentile** | -3.6 | -3.8 | -3.6 | -3.6 |
| **Tidal flat 50-percentile** | -2.1 | -2.6 | -2.3 | -2.4 |
| **Tidal flat 80-percentile** | -1.1 | -1.4 | -1.2 | -1.4 |

Based on these datasets, measured sediment elevation and sedimentation rate after 1900 AD in the Land of Saeftinghe ($Dh_{>1900}$ and $Dh_{>1900}/Dt_{>1900}$) were defined, using formulae 3 and 4.

$$Dh_{>1900} = H_{marsh\ T} - H_{flat\ 1902} \qquad (3)$$

*$H_{marsh\ T}$ : 50-percentile (1931, 1963, 1992 or 2004 AD) tidal marsh elevation at T = 1931, 1963, 1992 or 2004 AD*

*$H_{flat\ 1902}$ :50-percentile tidal flat elevation at T = 1902 AD (average of 1897/1907: dates of last embankments of intertidal area)*

$$Dt_{>1900} = T - 1902 \qquad (4)$$

*T : Date of elevation assessment (1931, 1963, 1992 or 2004 AD)*

According to our hypothesis, post-1900 AD sedimentation took place, above the level of the tidal flats at the time of the last embankment. South of the intertidal area, the last two embankments (which comprised almost the entire border of the present-day tidal marsh) were undertaken in 1897/1907 AD. Therefore the reference level of tidal flats was calculated, based on the MHWL of 1902 AD (as an average of 1897 and 1907 AD) and the 1931 AD (oldest available) 50-percentile tidal flat elevation. Sediment elevations were calculated afterwards by measuring the elevation difference of the typical tidal marsh elevations for 1931, 1963, 1992 and 2004 AD and the 1902 AD base level.

*3.3.2.2 Theoretically expected equilibrium sediment elevation and sedimentation rate before 1900 AD ($Dh_{<1900\ EQ}$ and $Dh_{<1900\ EQ}/Dt_{<1900}$) and after 1900 AD ($Dh_{>1900\ EQ}$ and $Dh_{>1900\ EQ}/Dt_{>1900}$)*

The elevations determined by the method explained above (both for the pre- and post-1900 AD period) were compared with the theoretical equilibrium elevation, in order to evaluate how far the actual elevations were from the equilibrium elevation, and to see to what extent the intertidal elevations were already evolved towards equilibrium or not.

Firstly, for the pre-1900 AD period, a comparison was made with the theoretically expected equilibrium sediment elevation and sedimentation rate before 1900 AD ($Dh_{<1900\ EQ}$ and $Dh_{<1900\ EQ}/Dt_{<1900}$), which was calculated using formulae 2 and 5.

$$\boldsymbol{Dh_{<1900\ EQ} = H_{marsh\ T\ (NEW)} - H_{flat\ T\ (OLD)}} \qquad \textbf{(5)}$$

*$H_{marsh\ T\ NEW}$ : Elevation of former tidal marsh zone, on date of new embankment (seaward of dike)*

*$H_{flat\ T\ OLD}$ : Elevation of former tidal flat zone, on date of old embankment (landward of dike)*

The theoretical sediment elevation is calculated through the difference between the expected elevation of the tidal marsh (at the date of a new embankment) and the elevation of the tidal flat on which sediments were deposited (at the date of the previous embankment). Elevations were calculated through the combination of Table 1 and Table 2. Based on the 20, 50 and 80 percentiles for typical equilibrium elevations in a stable tidal marsh (2004) and the historical MHWL, minimum, median and maximum historical sediment elevations for the tidal marsh were obtained for each time period. Minimum sediment elevation was calculated with the 20-percentile for former tidal marsh (the lowest possible elevation) seaward of the dikes and the 80-percentile for former tidal flat (the highest possible elevation), landward of the dike. Maximum sediment elevation was calculated with the 80-percentile (highest possible elevation) for the tidal marsh, and 20-percentile (lowest possible elevation) for the tidal flat; median sedimentation used 50-percentiles for both the tidal marsh and tidal flat.

Secondly, for the post-1900 AD period, comparison was made with the theoretically expected equilibrium sediment elevation and sedimentation rate after 1900 AD ($Dh_{>1900\ EQ}$ and $Dh_{>1900\ EQ}/Dt_{>1900}$), which was calculated using formulae 4 and 6. Formula 6 applies the relative *equilibrium* elevations of 2004 to each time step. This means absolute tidal marsh elevations were still variable, since MHWL differed over the four time periods.

$$Dh_{>1900\ EQ} = H_{marsh\ T(2004)} - H_{flat\ 1902} \qquad (6)$$

$H_{marsh\ T(2004)}$ *: 50-percentile (2004) tidal marsh elevation at T = 1931, 1963, 1992 or 2004*

$H_{flat\ 1902}$ *:50-percentile tidal flat elevation at T = 1902*

Note that minimum and maximum equilibrium sediment elevations and sedimentation rates were also calculated. For the minimum equilibria the 20-percentile of 2004 was used for tidal marsh elevation (minimum height) and the 80-percentile of 1931 (combined with the MHWL of 1902) for the elevation at the beginning of the sedimentation process (maximum height). For the maximum equilibria the 80-percentile of 2004 was used for tidal marsh elevation (maximum height) and the 20-percentile of 1931 (combined with the MHWL of 1902) for the elevation at the beginning of the sedimentation process (maximum height). Applying the values for these percentiles in formula 6 simply gives the respective minimum and maximum values for equilibrium elevation that could be calculated. The 50-percentiles are still regarded as giving the most likely equilibrium elevation.

*3.3.2.3 Horizontal (lateral) yearly growth of the tidal marsh before 1900 AD ($Dl_{<1900}/Dt_{<1900\ L}$)*

Finally, horizontal (lateral) yearly growth of the tidal marsh before 1900 AD ($Dl_{<1900}/Dt_{<1900\ L}$) was calculated for the time sections from 1700 AD onwards using formulae 7 and 8. Only tidal marshes that were not classified as either embankment, not-drained land higher than MHWS or as a tidal marsh in the previous reconstruction were included in the calculations (meaning no analysis for 1625 AD could be conducted).

$$Dl_{<1900} = S_{marsh}/L_{dike} \qquad (7)$$

*$S_{marsh}$ : tidal marsh surface seaward of dike*

*$L_{dike}$ : length of the seaward dike.*

$$Dt_{<1900} = 1700, 1791 \text{ or } 1852 \text{ AD - date of embankment} \qquad (8)$$

## 4. RESULTS AND DISCUSSION

### 4.1 GIS-reconstruction of intertidal landscape evolution, based on historical maps

The results of the various GIS-reconstructions are shown in Fig. 6.

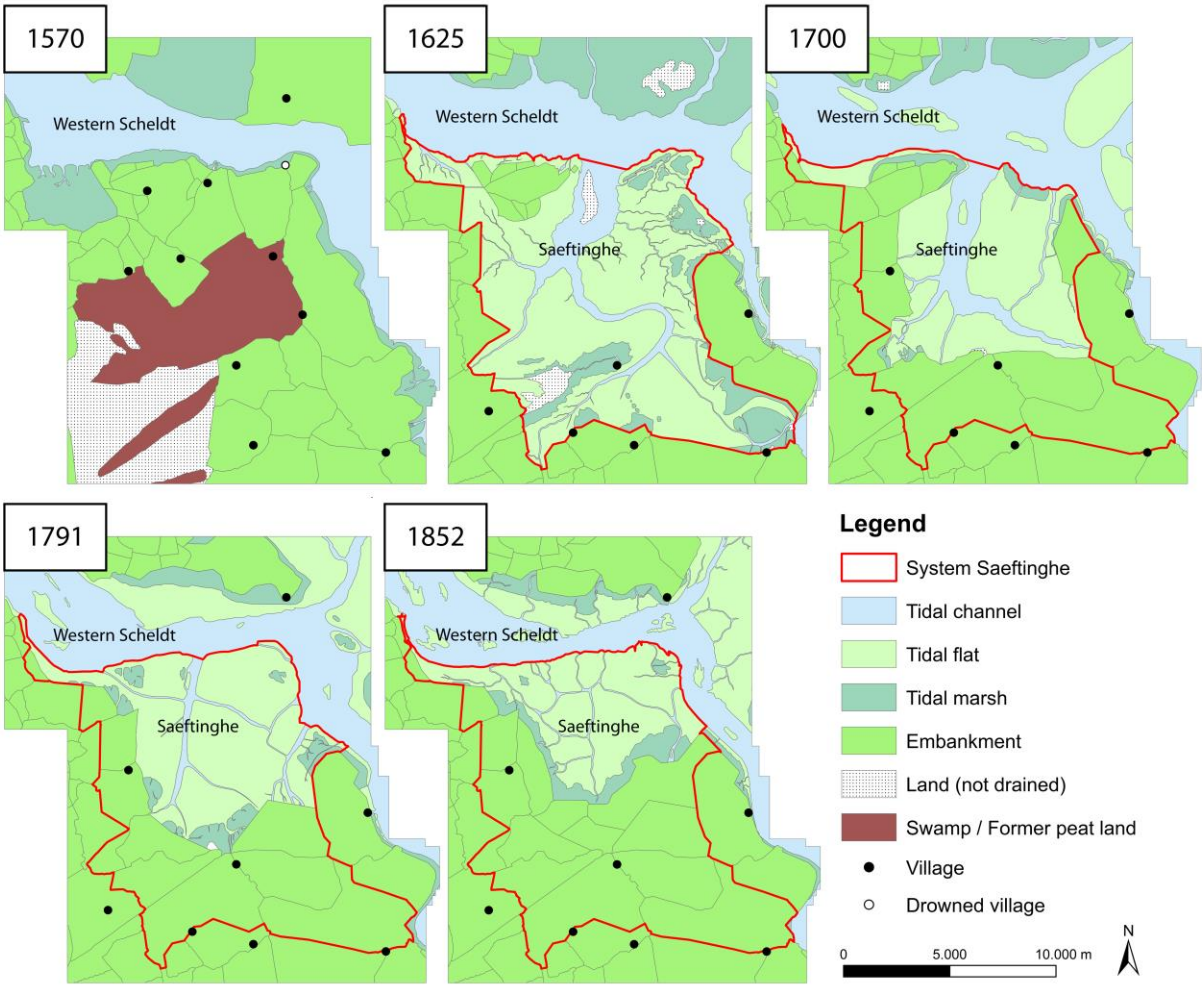


Fig. 6: GIS-reconstruction of the study area around 1570, 1625, 1700, 1791 and 1852 AD. [black-and-white in press, color version provided for web only]

The reconstruction of 1570 AD shows that most of the Waasland polder area and its surroundings were embanked. This was a result of embankment practices by large abbeys from the 10th or 11th century onwards, just south of the Western Scheldt (Guns, 2008) and the construction of dikes during centuries of late-medieval peat extraction, in the more central parts of the area (Augustyn, 1977; 1999). The central marshes ("moeren" or moorland) are left as a remnant of these extractions. More importantly, due to centuries of peat extraction and drainage, the surface of the embanked land had been lowered significantly (a process accelerated by soil (auto-) compaction), a process typical for the late-medieval Western

Scheldt estuary (Soens, 2013). This lowered surface, in combination with large scale intentional dike breaching for reasons of military inundations during the period of 1583-1585 AD (during the so-called Eighty Years' War), resulted in a dramatic drowning of the Waasland polder area and its surroundings. As a result, an extensive intertidal area was formed. The reconstruction shows a large tidal channel surrounded by an extensive tidal flat. Only a few areas were elevated higher and described as tidal marsh or unembanked land.

In the following period (1625-1700 AD), the area was re-embanked by subsequent (stepwise) embankment projects. As a result, the intertidal area decreased in size, but the main tidal channel remained intact, although its southeastern course changed significantly. Most of the remaining intertidal area was classified as tidal flat, except for small parts of tidal marshes in the north of the intertidal area. In the next century (1700-1791 AD), further re-embankments were undertaken. The intertidal area further decreased in size, and the tidal channel system appears to have silted up. Due to the larger embanked area, the volume of the intertidal area decreased, and as a result, the flood and ebb discharges going through the tidal channel system were reduced, causing sedimentation in the channels itself (D'Alpaos et al., 2006; Vandenbruwaene et al., 2012). Along the outer dikes of new embankments, zones of tidal marsh, formed due to the re-initiated sedimentation process, are found. Apparently there was always sufficient intertidal area left to avoid the possible effects of 'coastal squeeze' which can lead to (sometimes even complete) loss of tidal marsh. The process of tidal marsh formation persisted in the period of 1791-1852 AD. By then, almost the entire tidal flat was bordered by a tidal marsh, located along the outer dikes bordering the remaining intertidal area.

These results clearly prove that historical maps are a useful source of information (Jongepier et al., 2014, forthcoming). However, limitations are present in the form of the limited accuracy of some (small-scale) maps, and of course availability of maps might be limited if one particular date is a point of interest. For this study the intertidal area structure at the exact moment of embankment is most valuable but historical maps for that moment are not always available. This meant that additional sources of information were needed. One possible source of additional information is formed by soil maps, the potential for which is discussed in the next section.

### 4.2 Intertidal landscape reconstruction based on soil texture patterns

In order to assess to which extent the present-day soil charts can be used as an additional source of information for the historical intertidal area, we focused on the correlation between soil structure in later embankments (as given by the Belgian soil maps) and the former intertidal area which was contained in these embankments.

Results of the grain size analysis were plotted in a ternary diagram (Fig. 7). Note that samples with labels *clay*, *sandy loam* and *sand* are not categorised based on their position within the diagram, but according to their geographical location on the Belgian soil map. Only moderate variations in clay percentages were found, while percentages of silt and sand varied widely, which explains the linear distribution within the diagram.

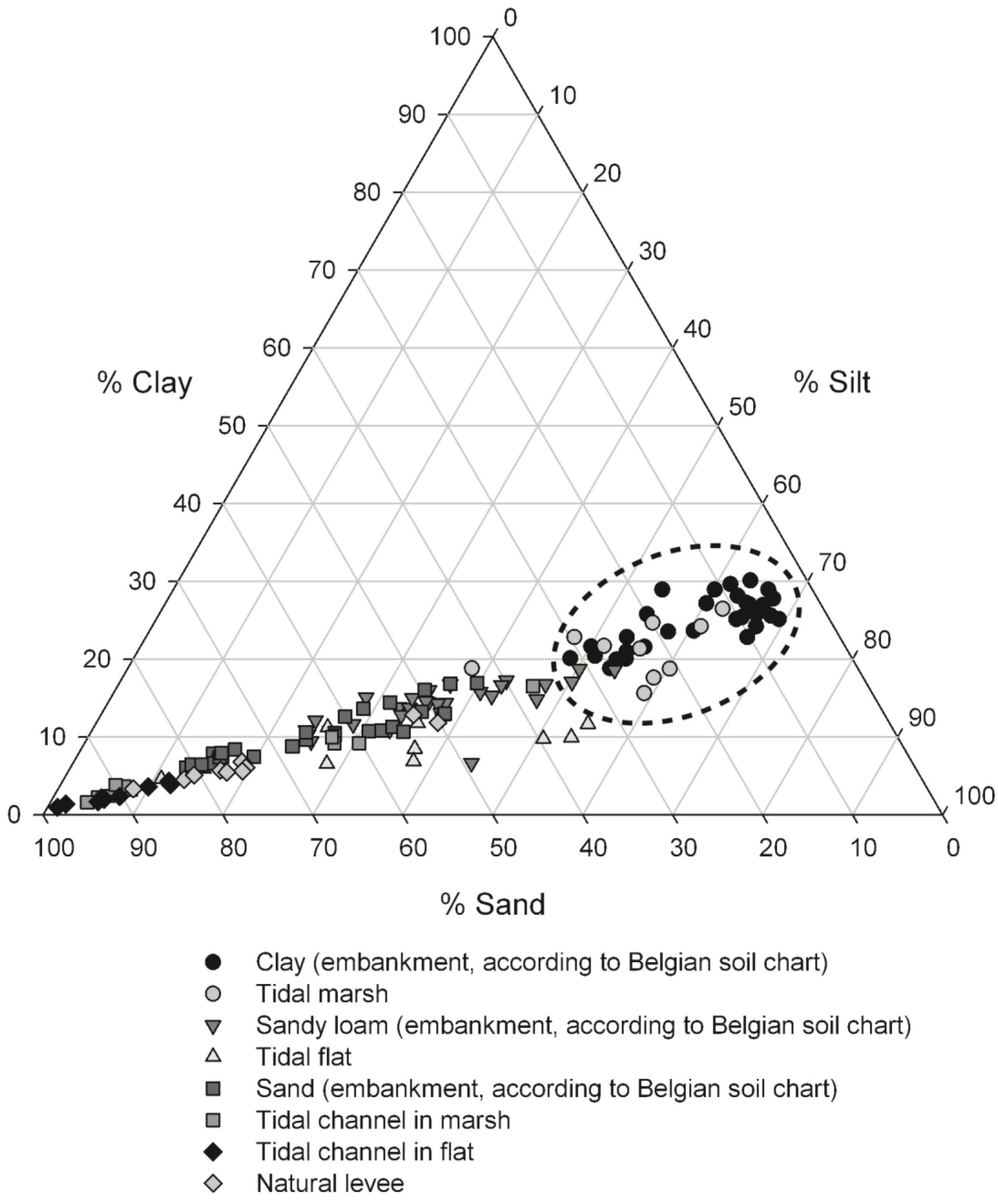


Fig. 7: Ternary plot for the soil samples in embankments (classified according to Belgian soil charts, plotted through measured percentages) and intertidal area.

Samples for categories *clay* (in the present-day embanked area) and *tidal marsh* (in the present-day remaining intertidal area) appear to be clustered (indicated by an oval in Fig. 7). Samples for *tidal channels in flat* and *natural levees* are found on the most sandy side of the diagram. The categories *sand* and *sandy loam* (in the present-day embanked area), *tidal channels in marsh* and *tidal flats* (in the present-day remaining intertidal area) are less clustered. For most samples, *tidal channels in marsh* display higher percentages of sand, and *tidal flats* higher percentages of silt. Splitting the results based on the percentages of clay, silt and sand resulted in three boxplots (Fig. 8). Within each of these components, the averages for each sample group were statistically analysed using non-parametric Mann-Whitney tests and ANOVA-tests (Table 3).

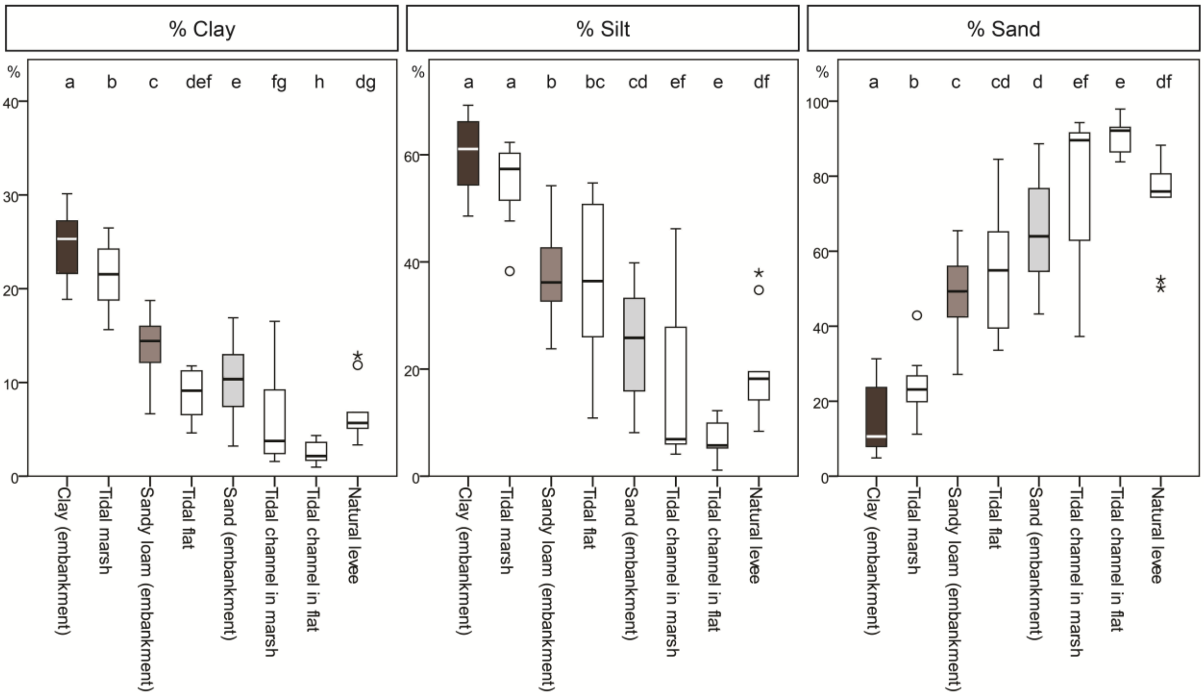


Fig. 8: Boxplots of percentages clay, silt and sand per sample category. Different letters (within the three subgroups) indicate significantly different means.

Table 3: P-values for <u>non</u>-significantly different means (p > 0,05)

| **In between categories:** | **% clay** | **% silt** | **% sand** |
|---|---|---|---|
| *Clay (embankment) and tidal marsh* | | *0.070* | |
| *Sandy loam (embankment) and tidal flat* | | *0.950* | *0.223* |
| *Sand (embankment) and tidal flat* | *0.248* | *0.070* | *0.179* |

| | | | |
|---|---|---|---|
| *Sand (embankment) and natural levee* | | *0.248* | *0.092* |
| *Tidal flat and tidal channel (in marsh)* | *0.076* | | |
| *Tidal flat and natural levee* | *0.290* | | *0.070* |
| *Tidal channel (in marsh) and tidal channel (in flat)* | | *0.174* | *0.096* |
| *Tidal channel (in marsh) and natural levee* | *0.112* | *0.226* | *0.226* |

These results show that, regarding the correlation between embankment and tidal marsh, based on percentages of clay, silt and sand, groups *clay* (in the embanked area) and *tidal marsh* (in the intertidal area) stand out. Non-significantly different means, however, for this pair are only found for a percentage of silt (p = 0.070, see Table 3). *Sandy loam* (embankment) and *tidal flat* have almost perfectly identical means (p = 0.950) when regarding percentages of silt, and do not differ significantly regarding percentages of sand (p = 0.223). However, *sand* (embankment ) and *tidal flat* (intertidal area) have not significantly different means for all three percentages. Regarding the grain size distribution within the intertidal area, a gradient with larger grain sizes close to the source of sediments (tidal channels) and finer sediments at the vegetated tidal marsh edges is noticeable. This is a result comparable to previously stated theories (Luternauer et al., 1995; Eisma, 1998; Woodroffe, 2003; Temmerman et al., 2004a). However, *tidal flats* and *tidal channels/natural levees* are not distinguishable based on percentages of clay (p = 0.076 / p = 0.290). In the embanked area, *clay*, *silt* and *sand* samples (as indicated by the Belgian soil maps) have significantly different means concerning all three percentages. This points (a) to a gradient from coarse to fine sediments from the seaward to the landward side of these embankments and (b) to correctness of the Belgian soil maps.

Interpretation of these results, in the light of finding a correlation between the embanked (former intertidal) area and present-day intertidal area, is not easy. Based on statistics solely, the relationship between *tidal marsh* and *clay* is not convincing. Similarities between *sand* and *tidal channels* are entirely absent. On the other hand, strong similarities between *tidal flat* and *sand/sandy loam* are found. Keeping in mind the results shown in the ternary diagram (Fig. 7), which showed the clustering of *clay* and *tidal* marsh and the similar grain size gradients in both embanked and intertidal areas, we venture to state that, based on the soil maps, at least an approximate division (tidal marsh vs. tidal flat/tidal channels) of the former tidal marsh can be made. Furthermore, the very fine clay sediments could simply not originate from anything other than the former tidal marsh since no historical evidence can be found that the embankment soils were imported from elsewhere.

In order to illustrate this, a similar division was applied to the *Nieuw-Arenbergpolder* (embanked in 1784 AD). Comparison was made in between an outstanding historical map which shows the division of tidal marsh, tidal flat and tidal channels just prior to embankment and the approximate division in between former tidal marsh and tidal flat/tidal channels (Fig. 9), based on the soil maps. The similarity is striking, except for the tidal channels which, according to the historical map, penetrate into the tidal marsh - an element which is lost in the soil map. Not surprisingly, percentages of tidal marsh (58%) and tidal flat/channel (42%) are identical for both sources.


Fig. 9: Comparison of zones of former tidal marsh and tidal flat/channel according to a historical map (ARA, Kaarten & Plans II, n° 8573) and Belgian soil map. [black-and-white in press, color version provided for web only]

A major limitation of this application of soil maps, however, is that they cannot be used to reconstruct the entire intertidal area at any given time. They only refer to the area enclosed by dikes during embankment, at the exact time of this embankment. For these reconstruction overviews, therefore, historical maps still provide the most useful source. For that reason historical maps have provided the information discussed in section 4.3.1. However, if information is only needed for the embanked area, and no historical maps with the correct date are available, the soil maps nonetheless provide a good source. Therefore, in this study, delimitations of former tidal marsh and former tidal flat, as used in section 4.3.2, are based on the soil maps.

## 4.3 Effect of stepwise embankment on the intertidal area

### *4.3.1 Effect on the surface percentages of tidal marshes, tidal flats and tidal channels*

Fig. 10 shows the evolution of surface areas of the tidal channels, flats and marshes in the studied intertidal area, as derived from the GIS-reconstructions from 1625 AD onwards. Next to the surfaces of the embanked area as calculated from the time sections of the GIS-reconstructions, a more detailed “embankment curve” is displayed. Clearly, the fastest rise in the embanked area is noticeable between 1625 and 1700 AD. After this period, the growth of the embanked area was more moderate. However, although the embankment surface between 1700 and 1791 AD did not rise spectacularly, the detailed curve shows that a more profound change took place since some embankments were lost during the same period.

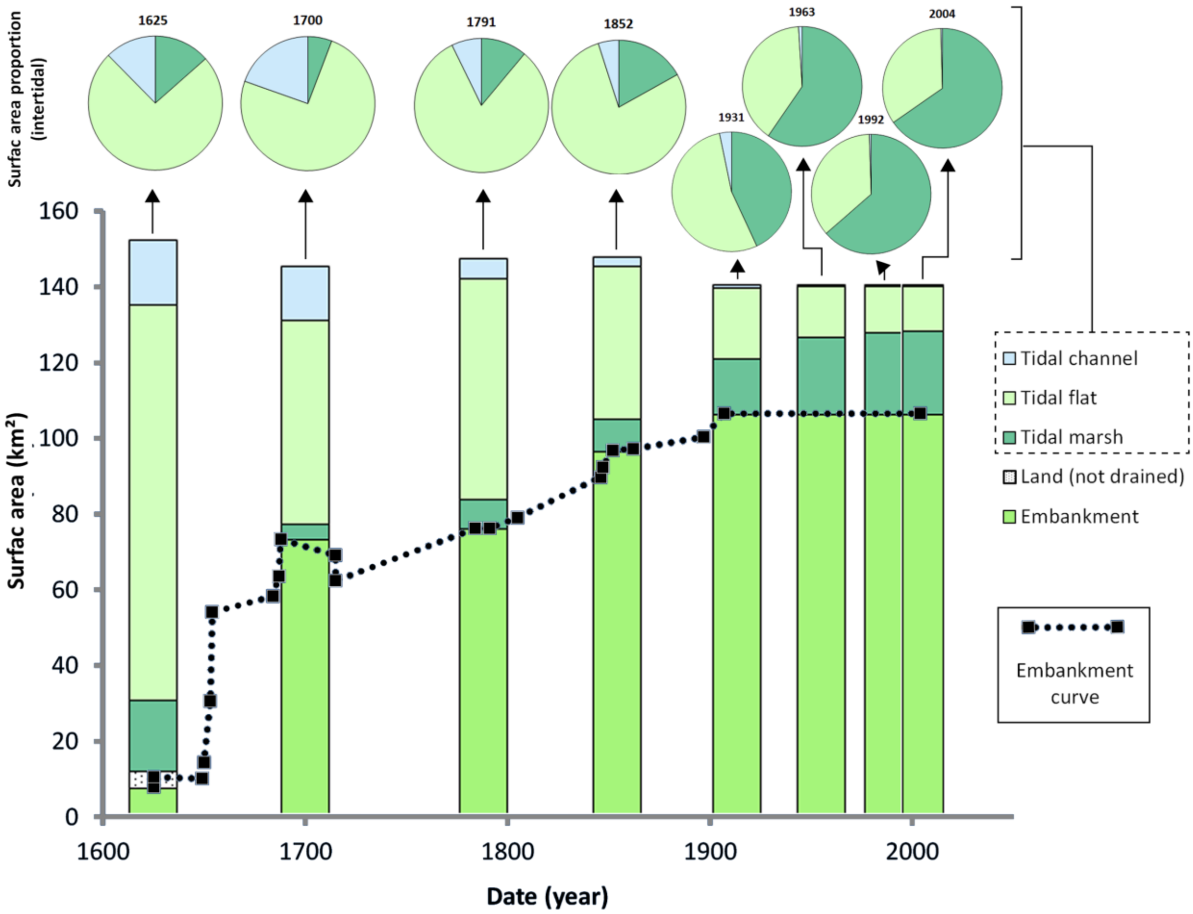


Fig. 10: Relative surfaces within the intertidal area (top) and absolute surfaces in "System Saeftinghe", combined with the detailed embankment areas (bottom). [black-and-white in press, color version provided for web only]

Apart from the decrease in absolute surface area of the intertidal area (by stepwise embankment), the evolution of the relative surface area of tidal channels, flats and marshes as proportional to the remaining total intertidal surface area, shows three characteristics (Fig. 10, top): (1) tidal flats are the dominant type during the entire period, (2) after a drop in tidal marsh surface area in between 1625-1700 AD, the proportional surface of tidal marsh enlarged while (3) the proportional surface of tidal channels decreased after 1700 AD. Comparing these pre-1900 AD data with more recent evolutions in the remaining intertidal area (Fig. 10, top) clearly shows tidal marsh percentages are significantly lower in the pre-

1900 AD period, during which most re-embankments took place. Each time a re-embankment took place, the existing tidal marshes along the borders of the intertidal area were embanked. These tidal marsh areas were easier to embank since they have a higher elevation than tidal flats and channels and hence flood less frequently. In addition to the tidal marsh, in the embankments we investigated in detail, a considerable surface of more seaward lying tidal flats and tidal channels was also embanked, but for other embankments in the estuary the dikes were sometimes built at the most seaward border of the tidal marsh, meaning almost no tidal flats were embanked. In both cases, however, the remaining intertidal area consisted mostly of tidal flats, and the process of vegetation growth and vertical sediment accretion in front of the newly built dikes was re-initiated.

The post-1900 AD period is characterized by a rapid change in surface area percentages in the earliest period (1931-1963 AD), followed by a rate of change which slowed down to almost zero in the latest period (1992-2004 AD). By then the largest part of the intertidal area was covered by tidal marshes that had finally reached their equilibrium state.

### *4.3.2 The response of the lateral and vertical tidal marsh accretion rates in front of the embankments on stepwise embankment*

By calculating tidal marsh elevation and sedimentation rates, using zones as defined by the Belgian soil map for the pre-1900 AD period, sediment elevation (Dh) and the sedimentation rate (Dh/Dt) are plotted in Fig. 11 against the time period over which the tidal marsh was formed (Dt).

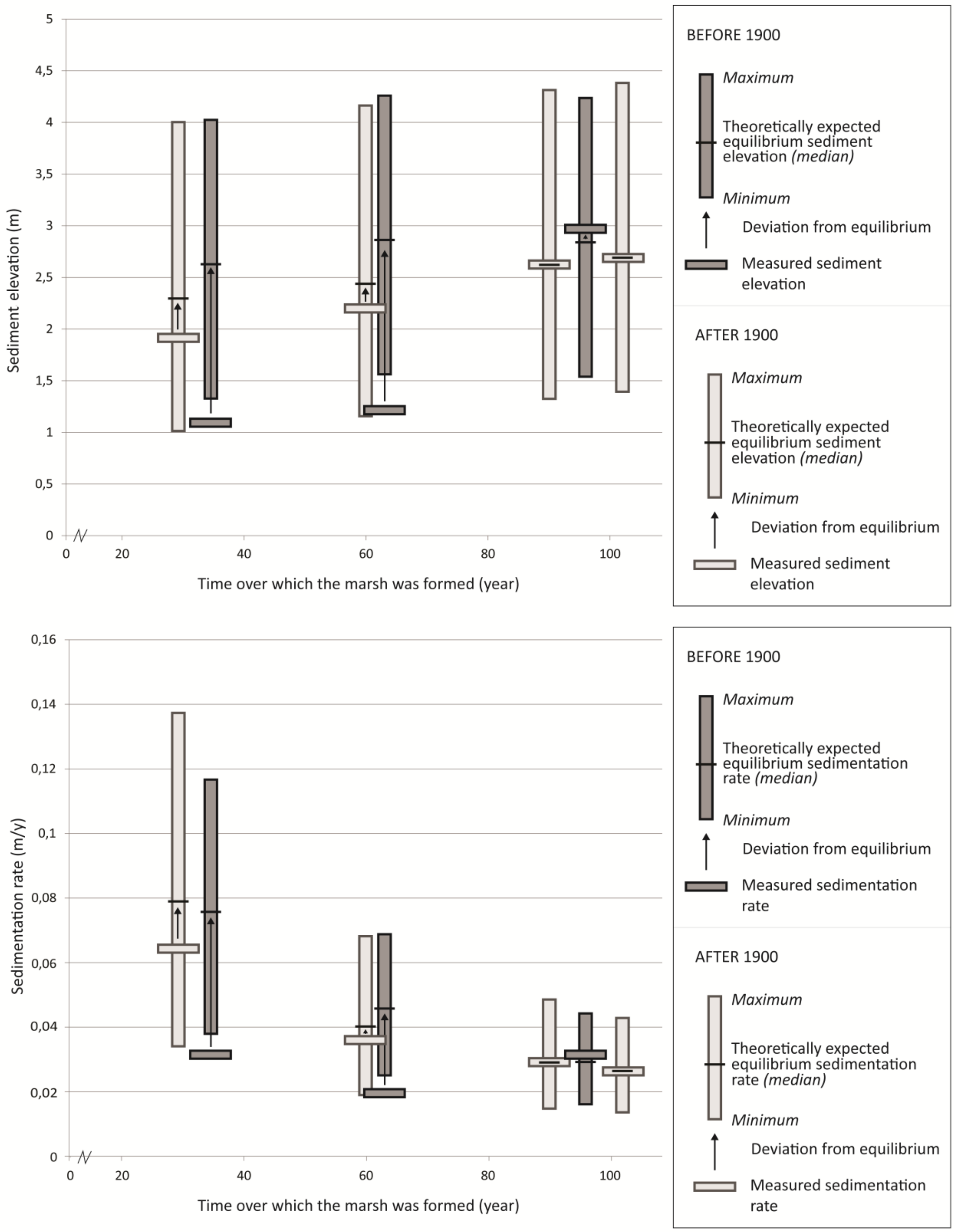


Fig. 11: Sediment elevation, plotted against time over which the tidal marsh was formed (top) and sedimentation rate (vertical), plotted against time time over which the tidal marsh was formed (bottom).

For Dt ≤ 62 years and for the time period before 1900 AD, measured tidal marsh elevations (Fig. 11, top) are located far below the theoretically expected equilibrium elevation. When Dt increases, the measured tidal marsh elevation becomes increasingly close to the theoretically expected equilibrium elevation, which is firstly reached at Dt = 96 years. These results can be compared to those of Pethick (1981), who investigated 14 tidal marshes on the north Norfolk coast ranging from 10 to over 2000 years in age. The reported asymptotic growth curve could not be confirmed for our pre-1900 AD data. Nevertheless, the fact that an equilibrium state can only be reached after longer time periods is supported by the pre-1900 findings. Pethick (1981) reported that ca. 200 years were needed for a tidal marsh to reach maturity, while acknowledging that these particular time frames are not necessarily applicable to other environments, since every intertidal area has its very specific circumstances (of which Suspended Sediment Concentrations and MHWL-rise form the major controlling factors for sedimentation processes, see also Temmerman et al. (2004b)). In the specific environment of our area of study, no equilibrium was reached if tidal marsh growth took place for time periods shorter than 62 to 96 years, due to successive embankments. Note that possible changes in historical suspended sediment concentrations could have had an impact on the exact equilibrium levels (Kirwan et al., 2010), but unfortunately no historical data on these concentrations within the Western Scheldt estuary is available.

For the intertidal area after 1900 AD, the same evolutionary pattern is visible: for shorter time differences (≤ 61 years), the theoretically expected equilibrium elevation is not yet reached, while for the longer time periods measured and theoretical equilibrium elevation coincide (firstly measured at Dt = 90 years). Again, no clear asymptotic curve was found, but equilibrium was reached in (approximately) the same time frame as for the pre-1900 AD period: 61 to 90 years after 1900, compared to 62 to 96 years for the pre-1900 AD period.

Logically, sedimentation rates (Fig. 11, bottom) do not reach the expected equilibrium rates for shorter time periods (≤ 61 (pre-1900 AD) or ≤ 62 post-1900 AD, with a larger difference before 1900 AD), while for longer periods (respectively ≥ 90 or ≥ 96) measured and expected equilibrium sedimentation rates correspond almost perfectly. The equilibrium rates would only have been found in every instance if a tidal marsh was able to reach its equilibrium height within 29 (post-1900 AD) to 34.5 (pre-1900 AD) years, which is (as described above) clearly not the case. Again, the asymptotical curve of the sedimentation rate over time, as reported by Pethick (1981); Allen (1990); French (1993) and Temmerman et al. (2004b), could not be confirmed by our data, especially not for the pre-1900 AD period. Comparing rates to those of Pethick (1981) shows sedimentation rates were far larger in our test-case. The north Norfolk tidal marshes had rates ranging from < 0.02 to 1.7 cm/year, while in our intertidal area rates of 1.9 to 3.2 cm/year were reported for the pre-1900 AD period and even 2.6 to 6.5 cm/year after 1900. A rise in MHWL (which may have an influence since tidal marshes have the tendency to keep an equilibrium elevation relative to MHWL (Temmerman et al., 2004b)) only explains part of this difference: for the pre-1900 AD period the MHWL-rise rise amounted to 0.36 to 0.58 cm/year, after 1900 AD 0.3 to 0.6 cm/year (van der Spek, 1997; Wang and Temmerman, 2013). On the other hand, the reported high rates explain why, in this specific test-case, the equilibrium was reached more quickly than in North Norfolk. Comparison with other historical (twentieth-century) sedimentation rates in the Western Scheldt estuary, also reveals the sedimentation rates in our study area are relatively large. Dyer et al. (2002) analyzed accretion rates for three tidal marshes, of which the *Waarde* tidal marsh should be most suitable for comparison, since it is located directly opposite to the *Saeftinghe* tidal marsh. Twentieth century sedimentation rates amounted to 0.5 to 3 cm per year, which again is lower than the calculations mentioned above (although our long-term sedimentation rate of 2.6 cm/year fits within the measured minimum and maximum). This could be explained by the fact the *Waarde* tidal marsh, which is described as ‘stable’ by the authors, probably was already close to an equilibrium state as early as 1944 AD, which is indicated by the fact the tidal channels did not change significantly ever since. As mentioned before it is expected sedimentation rates drop when a tidal marsh reaches it equilibrium.

The rate of lateral expansion of the tidal marsh areas (in meters per year) was plotted in Fig. 12 against the time over which the tidal marsh was formed (Dt).

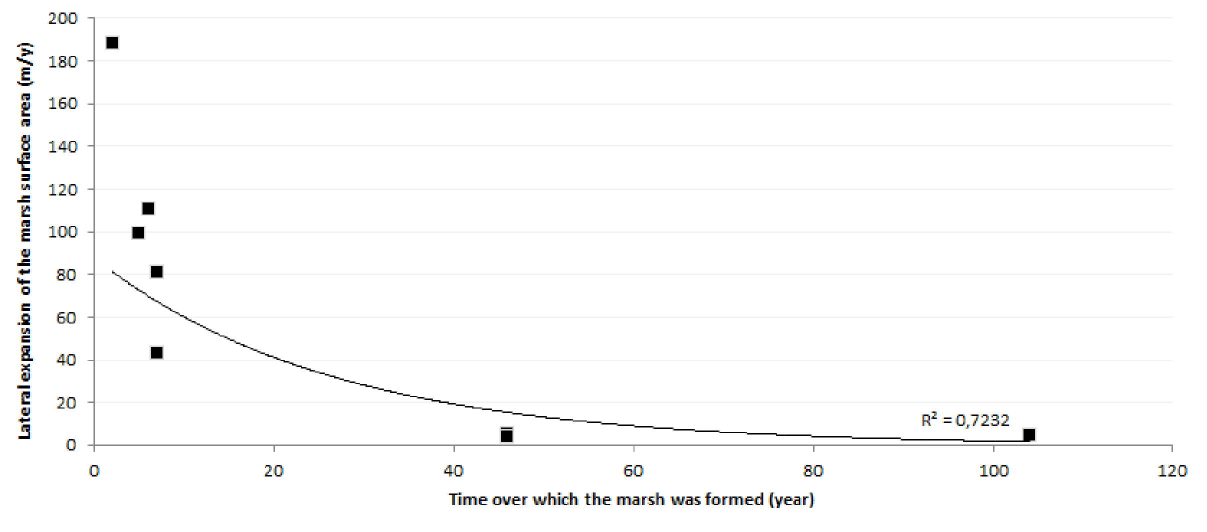


Fig. 12: Lateral growth per year of the tidal marsh, plotted against time since last embankment.

For short time periods (≤ 7 years), the yearly expansion rate was far higher, than for longer time periods over which the marsh was formed. Growth per year drops exponentially ($R^2$=0.7232). This exponential behavior for the lateral expansion rate (which was reported for vertical sedimentation rate by several authors, see above) is not commonly reported in the literature. Pethick (1981) even mentions that very little lateral development took place in the north Norfolk marshes. This equilibrium in lateral expansion rate of marshes is a point of interest that would benefit from further research.

## 5. CONCLUSIONS

Four major conclusions can be drawn from this study: (1) The long-term (since 1570 AD) response of an intertidal area to dike breaching and stepwise re-embankment could be reconstructed based on a combination of historical-geographical methods (critical GIS-analyses of historical maps) and geomorphological methods (soil texture mapping of embanked former intertidal areas). (2) Dike breaching and partial (stepwise) re-embankment are important driving mechanisms for the evolution of the resulting intertidal landscape towards new equilibrium conditions, but the new landscape equilibria can only be reached with a certain time lag. Here we investigated the time lags to reach equilibria in (a) tidal marsh surface area (relative to the total intertidal area surface) and (b) tidal marsh elevation (relative to mean high water level). (3) For the tidal marsh surface area, we found that subsequent embankments with a short time interval (on average once every 15 years in the study area, once every 21 years if combined embankments were considered as a single unit) prevented an equilibrium state being reached in the tidal marsh surface area. The tidal flat area remained excessively large compared to the tidal marsh area. Only for a period longer than 85 - 97 years after the last embankment (in this case study in the period after 1900 AD), had the expansion of the tidal marsh area reached a stable state within the studied intertidal area. (4) As regards the tidal marsh surface elevation, we found that it took between 62 and 96 years (before 1900 AD) or between 62 and 90 years (after 1900 AD) for it to reach an equilibrium. Hence for embankments that occurred with a shorter time interval, the tidal marshes that started to form on tidal flats in front of the sea dikes could not yet reach an equilibrium elevation.

Using a similar method as proposed in this article, future comparative research on other intertidal landscapes might determine and explain the degree of variation in these response time-scales, hence allowing for more general modelling. Furthermore, the same method could be applied to analyze historical elevation rates at the moment of drainage and embankment. Determining which intertidal areas had been drained in equilibrium conditions and which not, would highly benefit both our insight in the landscape history and the present-day geomorphology of coastal areas. Finally our findings on the response time scale of intertidal landscapes to dike breaching and (re-)embankment may be used as a historical reference for dike breaching projects (or so-called managed realignment projects) that are planned in the near future.

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## 7. APPENDIX: Historical maps used for the GIS-reconstructions

| Time section (AD) | Used for | Reference | Date displayed (AD) | MPE (meters) |
|---|---|---|---|---|
| 1570 | Studied intertidal area | RAG, Kaarten & plans, n° 2454 | +- 1570 | 722.40 |
| 1570 | Surroundings | Zelandicarum Insularum Exactissima Van Deventer | 1580 | 844.37 |
| 1625 | Studied intertidal area and surroundings | Kaart van de Vier Ambachten (Atlas van Loon, Scheepvaartmuseum Amsterdam) | +- 1620 | 1383.9 |
| 1625 | Studied intertidal area | RAG, Kaarten & plans, n° 2454 | 1629 | 346.94 |
| 1700 | Surroundings | ZA, Zelandia Iluustrata, n° 1303 | 1676 | 1507.06 |
| 1700 | Studied intertidal area | ZA, Atlas Hattinga, n°497(495) | 1687 | 53.63 |
| 1700 | Studied intertidal area | Map of Fricx (WAS) | 1706 | 1006.83 |
| 1700 | Surroundings | ZA, Atlas Hattinga, n°504 | | Not Assessed |
| 1791 | Studied intertidal area | ZA, Aanwinsten 1948, n°41 | 1791 | 103.68 |
| 1791 | Studied intertidal area | NADH, 4-OSK, n°V54 | 1792 | 365.99 |
| 1791 | Surroundings | ARA, Arenberg, n°842 | 1813 | 103.68 |
| 1790 | Surroundings | NADH, 4_VTH, n°2899 | 1818 | 812.96 |
| 1852 | Studied intertidal area | VanderMaelen (1:20.000) | 1850-1854 | Not assessed |
| 1852 | Studied intertidal area | Topografisch Militaire Kaart (color version) | 1836-1856 | Not assessed |

## 8. REFERENCES

Allen, J.R.L., 1990. Salt-marsh growth and stratification: a numerical model with special reference to the Severn Estuary, southwest Britain. Marine Geology, 95 (2), 77-96.

Allen, J.R.L., 1992. Large-scale textural patterns and sedimentary processes on tidal salt marshes in the Severn Estuary, southwest Britain. Sedimentary Geology, 81 (3-4), 299-318.

Allen, J.R.L., 2000. Morphodynamics of Holocene Salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. Quaternary Science Reviews, 19 (17-18), 1839-1840.
Allen, J.R.L., Haslett, S.K., 2006. Granulometric characterization and evaluation of annually banded mid-Holocene estuarine silts, Welsh Severn Estuary (UK): coastal change, sea level and climate. Quaternary Science Reviews, 25 (13-14), 1418-1446.
Ameryckx, J., 1974. Algemene bodemkunde: voor het technisch onderwijs, Gent.
Augustyn, B., 1977. Bijdrage tot het ontstaan en de vroegste geschiedenis van de Wase Polders van de oudste tijden tot circa 1400. Annalen van de Koninklijke oudheidkundige kring van het Land van Waas, 80 (50), 5-136.
Augustyn, B., 1999. De veenontginning (12de-16de eeuw). Geschiedenis van volk en land van Beveren. Gemeente Beveren, Beveren.
Baeteman, C., 2008. Radiocarbon dated sediment sequences from the Belgian coastal plain: testing the hypothesis of fluctuating or smooth late Holocene relative sea-level rise. The Holocene, 18 (8), 1219-1228.
Baeteman, C., Declercq, P.Y., 2002. A synthesis of early and middle Holocene coastal changes in the Belgian lowlands. Belgeo, 2002 (2), 77-107.
Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2010. The value of estuarine and coastal ecosystem services. Ecological Monographs, 81 (2), 169-193.
Bender, O., Boehmer, H.J., Jens, D., Schumacher, K.P., 2005. Using GIS to analyse long-term cultural landscape change in Southern Germany. Landscape and Urban Planning, 70 (1-2), 111-125.
Burningham, H., French, J., 2006. Morphodynamic behaviour of a mixed sand–gravel ebb-tidal delta: Deben estuary, Suffolk, UK. Marine Geology, 225 (1-4), 23-44.
Burningham, H., 2008. Contrasting geomorphic response to structural control: the Loughros estuaries, northwest Ireland. Geomorphology, 97 (3-4), 300-320.
Clarke, D.W., Boyle, J.F., Chiverrell, R.C., Lario, J., Plater, A.J., 2014. A sediment record of barrier estuary behaviour at the mesoscale: interpreting high-resolution particle size analysis. Geomorphology, 221, 51-68.
Coen, I., 2008. De eeuwige Schelde? Ontstaan en ontwikkeling van de Schelde. Waterbouwkundig Laboratorium, Borgerhout.
Cuvilliez, A., Deloffre, J., Lafite, R., Bessineton, C., 2009. Morphological responses of an estuarine intertidal mudflat to constructions since 1978 to 2005: The Seine estuary (France). Geomorphology, 104 (3-4), 165-174.
D'Alpaos, A., Lanzoni, S., Marani, M., Bonornetto, A., Cecconi, G., Rinaldo, A., 2007. Spontaneous tidal network formation within a constructed salt marsh: observations and morphodynamic modelling. Geomorphology, 91 (3-4), 186-197.
D'Alpaos, A., Lanzoni, S., Marani, M., Fagherazzi, S., Rinaldo, A., 2005. Tidal network ontogeny: channel initiation and early development. Journal of Geophysical Research-Earth Surface, 110 (F2).
D'Alpaos, A., Lanzoni, S., Mudd, S., Fagherazzi, S., D'Alpaos, A., Lanzoni, S., Mudd, S., Fagherazzi, S., 2006. Modeling the influence of hydroperiod and vegetation on the cross-sectional formation of tidal channels. Estuarine, Coastal and Shelf Science, 69 (3-4), 311-324.
de Boer, G., Carr, A.P., 1969. Early maps as historical evidence for coastal change. The Geographical Journal, 135 (1), 17-39.
Defina, A., Carniello, L., Fagherazzi, S., D'Alpaos, L., 2007. Self-organization of shallow basins in tidal flats and salt marshes. Journal of Geophysical Research-Earth Surface, 112 (F3).

Dias, J.M., Picado, A., 2011. Impact of morphologic anthropogenic and natural changes in estuarine tidal dynamics. Journal of Coastal Research, 1490-1494.

Dyer, F.M., Thomson, J., Croudace, I.W., Cox, R., Wadsworth, R.A., 2002. Records of change in salt marshes: a radiochronological study of three Westerschelde (SW Netherlands) marshes. Environmental Science and Technology, 36 (5), 854-861.

Eisma, D., 1998. Intertidal Deposits: River Mouths, Tidal Flats, and Coastal Lagoons. CRC Press, Boca Raton.

Fagherazzi, S., Carniello, L., D'Alpaos, L., Defina, A., 2006. Critical bifurcation of shallow microtidal landforms in tidal flats and salt marshes. Proceedings of the National Academy of Sciences of the United States of America, 103 (22), 8337-8341.

Fagherazzi, S., Kirwan, M.L., Mudd, S.M., Guntenspergen, G.R., Temmerman, S., D'Alpaos, A., van de Koppel, J., Rybczyk, J.M., Reyes, E., Craft, C., Clough, J., 2012. Numerical models of salt marsh evolution: ecological, geomorphic, and climatic factors. Reviews of Geophysics, 50 (1), RG1002.

Flemming, B., Ziegler, K., 1995. High-resolution grain size distribution patterns and textural trends in the backbarrier environment of Spiekeroog island (Southern North Sea. Senckenbergiana maritima, 26 (1-2), 1-24.

French, J.R., 1993. Numerical-simulation of vertical marsh grwoth and adjustment to accelerated sea-level rise, North Norfolk, UK. Earth Surface Processes and Landforms, 18 (1), 63-81.

French, J.R., 2001. Coastal defenses: processes, problems and solutions. Routeledge, London.

French, J.R., 2006. Tidal marsh sedimentation and resilience to environmental change: Exploratory modelling of tidal, sea-level and sediment supply forcing in predominantly allochthonous systems. Marine Geology, 235 (1-4), 119-136.

Galloway, J.A., 2009. Storm flooding, coastal defence and land use around the Thames estuary and tidal river c.1250-1450. Journal of Medieval History, 35 (2), 171-188.

Guns, P., 2008. Historische evolutie van het polderlandschap langs de linker Scheldeoever. Heruitgave editie 1973. Waterbouwkundig Laboratorium, Borgerhout.

Heirman, K., Missiaen, T., Vos, P., 2013. Holocene Palaeogeographical evolution of the Waasland Scheldepolders. Arch-Manche project, internal report, University of Ghent, Ghent.

Hoffmann, D., 2004. Holocene landscape development in the marshes of the West Coast of Schleswig-Holstein, Germany. Quaternary International, 112 (1), 29-36.

Hood, W.G., 2004. Indirect environmental effects of dikes on estuarine tidal channels: thinking outside of the dike for habitat restoration and monitoring. Estuaries, 27 (2), 273-282.

Ichoku, C., Chorowicz, J., 1994. A numerical approach to the analysis and classification of channel network patterns. Water Resources Research, 30 (2), 161-174.

Jacobs, P., De Ceukelaire, M., De Breuck, W., De Moor, G., 1993. Toelichtingen bij de geologische kaart van België, Vlaams gewest, Kaartblad (14) Lokeren Schaal 1:50 000. Departement Leefmilieu, Natuur en Energie. Dienst Natuurlijke Rijkdommen, pp. 46.

Jacobs, P., Polfliet, T., De Ceukelaire, M., Moerkerke, G., 2010a. Toelichtingen bij de geologische kaart van België, Vlaams gewest, Kaartblad (1-7) Essen - Kapellen Schaal 1:50 000. Departement Leefmilieu, Natuur en Energie. Dienst Natuurlijke Rijkdommen, pp. 44.

Jacobs, P., Polfliet, T., De Ceukelaire, M., Moerkerke, G., 2010b. Toelichtingen bij de geologische kaart van België, Vlaams gewest, Kaartblad (15) Antwerpen Schaal 1:50 000. Departement Leefmilieu, Natuur en Energie. Dienst Natuurlijke Rijkdommen, pp. 60.

Jenny, B., 2006. MapAnalyst - A digital tool for the analysis of the planimetric accuracy of historical maps. e-Perimetron, 1 (3), 239-245.
Jenny, B., Hurni, L., 2011. Studying cartographic heritage: analysis and visualization of geometric distortions. Computers & Graphics, 35, 402-411.
Jenny, B., Weber, A., Hurni, L., 2007. Visualising the planimetric accuracy of historical maps with MapAnalyst. Cartographica, 42 (1), 89-94.
Jongepier, I., Soens, T., Temmerman, S., Missiaen, T., 2014, forthcoming. Assessing the planimetric accuracy of historical maps (sixteenth to nineteenth centuries). New methods and potential for coastal landscape reconstruction. The Cartographic Journal.
Kirwan, M.L., Guntenspergen, G.R., D'Alpaos, A., Morris, J.T., Mudd, S.M., Temmerman, S., 2010. Limits on the adaptability of coastal marshes to rising sea level. Geophysical Research Letters, 37 (23), L23401.
Lloyd, R., Gilmartin, P., 1987. The South Carolina coastline on historical maps: a cartometric analysis. The Cartographic Journal, 24 (1), 19-26.
Long, A.J., Waller, M.P., Stupples, P., 2006. Driving mechanisms of coastal change: peat compaction and the destruction of late Holocene coastal wetlands. Marine Geology, 225, 63-84.
Luternauer, J.L., Atkins, R.J., Moody, A.I., Williams, H.F.L., Gibson, J.W., 1995. Salt Marshes. In: Perillo, G.M.E. (Ed.), Geomorphology and sedimentology of estuaries. Elsevier Science, Amsterdam, pp. 307-332.
Maio, C.V., Tenenbaum, D.E., Brown, C.J., Mastone, V.T., Gontz, A.M., 2013. Application of geographic information technologies to historical landscape reconstruction and military terrain analysis of an American Revolution Battlefield: Preservation potential of historic lands in urbanized settings, Boston, Massachusetts, USA. Journal of Cultural Heritage, 14 (4), 317-331.
Marani, M., D'Alpaos, A., Lanzoni, S., Carniello, L., Rinaldo, A., 2010. The importance of being coupled: Stable states and catastrophic shifts in tidal biomorphodynamics. Journal of Geophysical Research-Earth Surface, 115.
Martinez, C., Quezada, M., Rubio, P., 2011. Historical changes in the shoreline and littoral processes on a headland bay beach in central Chile. Geomorphology, 135 (1-2), 80-96.
McGlathery, K.J., Reidenbach, M.A., D'Odorico, P., Fagherazzi, S., Pace, M.L., Porter, J.H., 2013. Nonlinear dynamics and alternative stable states in shallow coastal systems. Oceanography, 26 (3), 220-231.
Meier, D., 2013. From nature to culture: landscape and settlement history of the North-Sea coast of Schleswig Holstein, Germany. In: Thoen, E., Borger, G.J., De Kraker, A., Soens, T., Tys, D., Vervaet, L., Weerts, H.J.T. (Eds.), Landscapes or seascapes? The history of the coastal environment in the North Sea area reconsidered. CORN Publication Series. Brepols, Turnhout, pp. 111-127.
Middelkoop, H., Asselman, N.E.M., 1998. Spatial variability of floodplain sedimentation at the event scale in the Rhine-Meuse delta, the Netherlands. Earth Surface Processes and Landforms, 23 (6), 561-573.
Novakowski, K.I., Torres, R., Gardner, L.R., Voulgaris, G., 2004. Geomorphic analysis of tidal creek networks. Water Resources Research, 40 (5), 1-13.
Pethick, J.S., 1981. Long-term accretion rates on tidal salt marshes. Journal of Sedimentary Petrology, 51 (2), 571-577.
Rahman, R., Plater, A.J. (2014) Particle-size evidence of estuary evolution: a rapid and diagnostic tool for determining the nature of recent saltmarsh accretion. Geomorphology, 213, 139-152.

Rippon, S., 2000. The transformation of coastal wetlands: exploitation and management of marshland landscapes in north west Europe during the roman and medieval periods. British Academy, London.
Shi, Z., Lamb, H.F., Collin, R.L., 1995. Geomorphic change of saltmarsh tidal creek networks in the Dyfi Estuary, Wales. Marine Geology, 128 (1-2), 73-83.
Soens, T., 2013. The origins of the Western Scheldt. Environmental transformation, storm surges and human agency in the Flemish coastal plain (1250-1600). In: Thoen, E., Borger, G.J., De Kraker, A., Soens, T., Tys, D., Vervaet, L., Weerts, H.J.T. (Eds.), Landscapes or seascapes? The history of the coastal environment in the North Sea area reconsidered. CORN Publication Series. Brepols, Turnhout, pp. 287-312.
Stankoviansky, M., 2003. Historical evolution of permanent gullies in the Myjava Hill Land, Slovakia. Catena, 51 (3-4), 223-239.
Stumpf, R.P., 1983. The process of sedimentation on the surface of a salt marsh. Estuarine, Coastal and Shelf Science, 17 (5), 495-508.
Temmerman, S., Govers, G., Meire, P., Wartel, S., 2003. Modelling long-term tidal marsh growth under changing tidal conditions and suspended sediment concentrations, Scheldt estuary, Belgium. Marine Geology, 193 (1-2), 151-169.
Temmerman, S., Govers, G., Meire, P., Wartel, S., 2004a. Simulating the long-term development of levee-basin topography on tidal marshes. Geomorphology, 63 (1-2), 39-55.
Temmerman, S., Govers, G., Wartel, S., Meire, P., 2004b. Modelling estuarine variations in tidal marsh sedimentation: response to changing sea level and suspended sediment concentrations. Marine Geology, 212 (1-4), 1-19.
Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. Nature, 504 (7478), 79-83.
Timár, G., Székely, B., Molnár, G., Ferencz, C., Kern, A., Galambos, C., Gercsák, G., Zentai, L., 2008. Combination of historical maps and satellite images of the Banat region - Re-appearance of an old wetland area. Global and Planetary Change, 62 (1-2), 29-38.
Uribelarrea, D., Perez-Gonzalez, A., Benito, G., 2003. Channel changes in the Jararna and Tagus rivers (central Spain) over the past 500 years. Quaternary Science Reviews, 22 (20), 2209-2221.
van der Spek, A.J.F., 1997. Tidal asymmetry and long-term evolution of Holocene tidal basins in The Netherlands: simulation of palaeo-tides in the Schelde estuary. Marine Geology, 141, 71-90.
Vandenbruwaene, W., Bouma, T.J., Meire, P., Temmerman, S., 2013. Bio-geomorphic effects on tidal channel evolution: impact of vegetation establishment and tidal prism change. Earth Surface Processes and Landforms, 38 (2), 122-132.
Vandenbruwaene, W., Meire, P., Temmerman, S., 2012. Formation and evolution of a tidal channel network within a constructed tidal marsh. Geomorphology, 151-152, 114-125.
Verbruggen, C., Denys, L., Kiden, P., 1991. Paleo-ecologische en geomorfologische evolutie van Laag- en Midden-België tijdens het Laat-Kwartair. De Aardrijkskunde, 3, 357-376.
Vos, P.C., van Heeringen, R.M., 1997. Holocene geology and occupation history of the province of Zeeland. In: Fischer, M.M. (Ed.), Holocene evolution of Zeeland (SW Netherlands). Netherlands Institute of Applied Geoscience TNO, Haarlem, pp. 3-109.
Wang, C., Temmerman, S., 2013. Does biogeomorphic feedback lead to abrupt shifts between alternative landscape states?: An empirical study on intertidal flats and marshes. Journal of Geophysical Research: Earth Surface, 118 (1), 229-240.

Wang, Y., Yu, Q., Gao, S., 2013. Modeling interrelationships between morphological evolution and grain-size trends in back-barrier tidal basins of the East Frisian Wadden Sea. Geo-Marine Letters, 34 (1), 37-49.

Woodroffe, C.D., 2003. Coasts: form, process and evolution. Cambridge University Press, Cambridge.

Yang, S.L., Li, H., Ysebaert, T., Bouma, T.J., Zhang, W.X., Wang, Y.Y., Li, P., Li, M., Ding, P.X., 2008. Spatial and temporal variations in sediment grain size in tidal wetlands, Yangtze Delta: on the role of physical and biotic controls. Estuarine, Coastal and Shelf Science, 77 (4), 657-671.

Zawiejska, J., Wyzga, B., 2010. Twentieth-century channel change on the Dunajec River, southern Poland: patterns, causes and controls. Geomorphology, 117 (3-4), 234-246.

Zeff, M.L., 1988. Sedimentation in a salt marsh-tidal channel system, southern New Jersey. Marine Geology, 82 (1-2), 33-48.