

Morphological instability in restored intertidal flats: How anthropogenic structures drive early-stage evolution

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Abstract

Coastal wetlands play a crucial role because of their wide range of ecosystem services, including coastal protection, carbon sequestration and biodiversity support. However, these environments are increasingly threatened by land reclamation, sea-level rise and sediment supply reductions, leading to widespread degradation. Managed realignment has emerged as a nature-based solution, allowing tidal processes to restore coastal wetland function. While extensively studied in natural settings, the evolution of restored intertidal flats remains poorly understood. This study examines sediment deposition, vertical accretion and morphological evolution in three human-induced intertidal flats across different tidal environments: Barbamarco Lagoon (microtidal, Italy), Perkpolder (macrotidal, The Netherlands) and Converse (hypertidal, Canada). The analyses followed the same procedure in all environments and were achieved through the use of sediment traps and digital elevation models, integrated with river and tidal records. Results indicate that during the early years of development, managed realignment sites experience rapid accretion in unusual locations of the intertidal flats (e.g. inside channels) and high erosion of artificial structures (e.g. creeks, inlets). This morphological instability influences sediment redistribution and intertidal flat evolution, potentially leading to self-cannibalisation, where erosion of the artificial structures feed the system itself. These findings highlight the importance of long-term monitoring to assess the sustainability of restored intertidal flats and improve predictions of their development. Future research should focus on how coastal wetland design influences long-term evolution and how sediment supply, tidal range and human interventions shape their resilience in the face of climate change.

KEYWORDS

building-with-nature, coastal wetland restoration, intertidal flat, managed realignment, salt marsh, sediment deposition

1 | INTRODUCTION

Coastal wetlands are complex environments that include a wide range of subsystems. The most common and relevant are the intertidal flats, defined as low-lying areas containing extended muddy or sandy

unconsolidated and unvegetated sediments that accumulate within the intertidal fringe, including the supratidal zone (Amos, 1995; Klein, 1985), and the marshes, which are areas characterised by vegetation able to cope with high salinity as well as subaerial exposure and usually located at higher elevations compared to the intertidal flats.

[Corrections made in 11 March 2026. After the first online publication, the second affiliation for the authors Samantha Crowell, Megan Elliott, and Danika van Proosdij has been corrected in this version.]

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These environments play a crucial role in attenuating storm waves, surges (Zhang et al., 2012; Möller et al., 2014; Smolders et al., 2015; Boutwell & Westra, 2015; Stark et al., 2015; Vuik, Jonkman, & Van Vuren, 2016; Leonardi et al., 2018) and sea-level rise (SLR) (Fagherazzi et al., 2012; Kirwan et al., 2010). They allow organic carbon accumulation (Campbell et al., 2022; Mcleod et al., 2011), supporting the local economy (Weis, 2016) and the ecosystem (Barbier et al., 2011; Boesch & Turner, 1984; MacKenzie & Dionne, 2008). A large variety of physical-biogeochemical factors (e.g. plant distribution, sediment deposition and soil content) influence the evolution of these systems, which in turn are controlled by three main components: the tidal range, the wave regime and, if present, the river discharge (i.e. deltas and estuaries). Tidal range is a key driver of wetland evolution, influencing the hydroperiod (French, 1993; Cahoon & Reed, 1995), the morphology and size of intertidal flats and marshes (Murray et al., 2008), the sediment transport and deposition (e.g. Pethick, 1981; Rahman & Plater, 2014), and morphological features, such as tidal channels (Coco et al., 2013). As tidal range increases from micro (<2 m) to mesotidal (<4 m) to macrotidal (>4 m), the daily vertical variations in sea level reshape both wetland morphology and ecosystem dynamics (Pratolongo et al., 2019), while stronger tidal currents can transport larger sediment volumes across the system (Chen et al., 2005; Xie et al., 2023). The presence of a river influences the evolution of intertidal flats and marshes as well, for example by altering the salinity distribution (e.g. Maicu et al., 2018), acting as a sediment supply (e.g. Brunetta & Ciavola, 2024), and influencing sediment transport and deposition (e.g. Day et al., 2011).

During the last century, coastal wetlands have declined globally because of land reclamation (e.g. van Maren et al., 2016; Wang et al., 2015), SLR (Temmerman & Kirwan, 2015) and low sediment input (e.g. Paola et al., 2011). As these habitats disappear, so do their critical ecosystem services. Therefore, management strategies should aim to promote a sustainable co-existence between natural ecosystems and anthropogenic activities. In fact, the environmental loss is not the only issue of these areas. Coastal defence using traditional infrastructures (e.g. dykes and seawalls) is proving to be inadequate because of long-term effects, presenting more disadvantages than benefits (Temmerman et al., 2013). Numerous studies have demonstrated that these structures lead to a series of negative consequences, such as risk of casualties and structural damages when defences fail (Smits, Nienhuis, & Saeijs, 2006; Van Koningsveld et al., 2008); undesired ecological deterioration, including tidal environment erosion and occurrences of toxic algal blooms (Verspagen et al., 2006); and changes in sediment patterns along the coastlines (Amaroli et al., 2012).

Managed realignment in coastal wetlands is becoming a common strategy to aid for both issues (i.e. wetlands loss and hard engineering structures) based on allowing the sea to submerge a portion of coastal areas to form a new intertidal environment (Cox et al., 2022). This strategy was adopted in several coastal wetlands worldwide; for example, the most famous are in Tollesbury and the Orplands, located in the Blackwater Estuary (Essex, UK) (Garbutt et al., 2006; Spencer et al., 2008). Other examples can be found in the Perkpolder tidal basin located in the Scheldt estuary (Zeeland, The Netherlands) (Brunetta, de Paiva, & Ciavola, 2019; Cao et al., 2021) or in the Bay of Fundy (Nova Scotia, Canada) (Crowell et al., 2025; Wollenberg, Ollerhead, & Chmura, 2018). The formation of new tidal environments generally aims for the development of a marsh, because marshes have the capability to

reduce storm waves (Barbier et al., 2008; Bouma et al., 2014; Gedan et al., 2011; Shepard, Crain, & Beck, 2011), storm surges (Zhang et al., 2012; Boutwell & Westra, 2015; Stark et al., 2015; Leonardi et al., 2018) and to keep pace with SLR (Kirwan et al., 2010; Fagherazzi et al., 2012). However, these restored intertidal flats undergo a different evolution compared to natural tidal flats, both because they are young (e.g. act as a sink for sediment) and are characterised by artificial features (e.g. creeks and inlets). Therefore, there is a need to understand how these environments will evolve in time and how differently they behave compared to their natural counterpart.

This study combines analyses on sediment deposition, vertical changes and sediment budget carried out in three study cases located in different environments that cover the full spectrum of tidal range (i.e. from microtidal to hypertidal): (i) the 'unmanaged realignment' of the microtidal flat (i.e. ~0.5 m) of the Barbamarco Lagoon (Po Delta, Italy); (ii) the managed realignment of macrotidal flat (i.e. ~4.6 m) of Perkpolder (Scheldt Estuary, The Netherlands) and (iii) the managed realignment of the hypertidal flat (i.e. ~12 m; Archer, 2013) of Converse (Nova Scotia, Canada).

The principal aims of this study are: (i) to understand how the artificial structures (i.e. channels and breaches) of managed realignment sites influence their evolution during their early years of development, (ii) to obtain a worldwide dataset which presents a full range of sediment deposition and vertical changes for the main type of tidal environment, and (iii) to discuss the findings of the previous points with literature dataset and other case studies that presented similar evolution.

2 | STUDY SITES

2.1 | Sites selection

The three study sites (i.e. Barbamarco Lagoon, Perkpolder and Converse) were selected to represent the main ranges of the global tidal spectrum while sharing fundamental morphodynamic boundary conditions. Although these sites are dominated by different processes (i.e. river vs tidal currents), these study cases have several features in common:

- i. Following the classification of Cox et al. (2022), all three sites originated from a 'diversion' event where an anthropogenic breach (intentional or accidental) re-connected a sediment-starved area to a rich sediment source. Whether the source was marine (i.e. Perkpolder and Converse) or riverine/estuarine (i.e. Barbamarco Lagoon), the triggering mechanism is identical; therefore, they share a common genesis. The only difference is that the study area of the Barbamarco Lagoon can be considered as a 'passive' natural restoration (see Section 2.2 for more detail; Gann et al., 2019), while the Perkpolder and Converse projects are 'active' natural restoration (see Sections 2.3 and 2.4 for more detail).
- ii. All sites are young ecosystems in their early stage. The site located in the Barbamarco Lagoon developed post-2000, the Perkpolder one developed post-2015, and the Converse one post-2018. This allows for a comparison of the initial morphological adjustments after the beach.
- iii. All sites are sheltered environments; therefore, the wave activity is low and negligible compared to the other processes (see Section 2.1.1 for more detail).

- iv. The study areas are characterised by high sediment supply. The Po River transports a large amount of sediment during floods (Brunetta, Duo, & Ciavola, 2021; Tesi et al., 2011); the Perkpolder site receives sediment from the Scheldt turbidity maximum (Chen et al., 2005); and the high flocculation of silt in the Bay of Fundy allows strong sedimentation in Converse (van Proosdij et al., 1999; van Proosdij, Davidson-Arnott, & Ollerhead, 2006).
- v. Since all sites are at the beginning of their development, they are all predominantly unvegetated intertidal flats (or sparsely vegetated), allowing the study to focus purely on hydro-morphological processes.

Furthermore, to better identify the position of the intertidal flats within the tidal spectrum, the classification of Amos (1995) was applied. The elevation of each tidal flat (i.e. typical min and max elevations referred to the Lowest Astronomical Tide) was normalised against its respective maximum tidal range. Despite the vast differences in absolute tidal range, all three study sites occupy a comparable position within the intertidal frame. The intertidal flat of the Barbamarco Lagoon has a relative range mainly within 0.5 and 0.75, covering almost the whole intertidal fringe but mostly locating the flat into the Middle Tidal Flats. The intertidal flat of Perkpolder falls within 0.38 to 0.68 relative range, classifying it within the Middle Tidal Flats. The intertidal flat of Converse is the highest compared to the others (0.85–0.97), locating the study area between higher flats and the supratidal zone.

2.1.1 | Considerations on waves and wind influence

Although wind-wave erosion is an important morphological process in open-coast intertidal flats and salt marshes (e.g. Leonardi & Fagherazzi, 2015), the effect can be considered as low and negligible in these study cases because of the specific geomorphic settings. The intertidal flat of the Barbamarco Lagoon is exposed to major wind from NNE and SE (Bora and Sirocco) (Maicu et al., 2018) and is protected by levees on the eastern side (i.e. no fetch), suggesting a low effect owing to wind waves (see Section 2.2 for detail). The Perkpolder basin is exposed to 1 km of fetch at maximum and, although has a relatively high percentage of sand (40% on total average), the high mud content allows the sediment mixture to maintain cohesive properties, therefore higher critical shear stresses compared to non-cohesive sands (Van Ledden, 2003). Furthermore, this enclosed basin is characterised by shallow depths, thus the formation of high-energy waves capable of causing resuspension is low compared to the effects of tidal currents (Fagherazzi & Wiberg, 2009; see Section 2.3 for detail). The study case of Converse is highly silty and has a complex structure that makes the fetch relatively short (see Section 2.4 for detail).

2.2 | Barbamarco Lagoon (Po River Delta, Italy)

The Po Delta (Italy) is a microtidal deltaic system characterised by a mixed, mostly semi-diurnal tide with an average tidal range of about 0.5 m and a spring-tidal range of 1 m. Its evolution was highly

influenced by both natural and anthropic processes (Bondesan, 1990; Cencini, 1998; Simeoni & Corbau, 2009), in particular, after the 'Porto Viro' bypass, a heavy human intervention made under the Venetian Republic in 1604, which diverted the delta to the current location (Stefani & Vincenzi, 2005) and making it one of the largest anthropic deltas in the world (Maselli & Trincardi, 2013). The combination of high subsidence (Caputo, Pieri, & Unguendoli, 1970; Fabris, 2019), heavy flooding (Piccoli, 1976), coastal storms (Perini et al., 2011) and human interventions (Billi & Fazzini, 2017; Bondesan & Simeoni, 1983; Dal Cin, 1983; Dal Cin & Simeoni, 1984) caused a severe coastline retreat and the submersion of large areas of agricultural fields. In 2010, the trend reversed, and the delta entered a phase of progradation (Bezzi et al., 2021; Ninfo, Ciavola, & Billi, 2018).

The Po Delta, which extends for 691 km² along 90 km of coastline (Figure 1a), has five principal branches (from north to south, Po di Maistra, Pila, Tolle, Donzella or Gnocca, and Goro). The study case is located in the southernmost part of the Barbamarco Lagoon, which extends between the central branch of the Po della Pila and the Po di Maistra (Figure 1b). The study area is an ~8 ha young intertidal flat that has been developing during the last 20 years after two channels were dug in order to connect the harbours of Pila (Figure 1c). Both channels are separated from the intertidal flat by the presence of wild reeds that have been established on the channel levees. These channels were slowly breached between the 2000 and 2003 by river floods that created two breaches located on the east channel and one on the west channel connecting the river to the flat (Brunetta & Ciavola, 2024; Brunetta, Duo, & Ciavola, 2021, 2025). The creation and evolution of this intertidal flat follow the same approach of a managed realignment, specifically developed after a river diversion (Cox et al., 2022). The breaches occurred naturally, but the channels that connected this part of the lagoon to the river derive from human intervention. This 'unmanaged realignment' can be associated with a 'passive' natural regeneration, where the removal of a stress factor or, in this case, of a physical condition allows natural processes to recreate a lost ecosystem (Gann et al., 2019). In short, anthropogenic modifications (i.e. channel excavation) unintentionally triggered the regeneration of an intertidal flats in an area that was historically intertidal.

The study area, and the progradation of the deltaic system as well, is highly dependent on river floods (Brunetta, Duo, & Ciavola, 2021; Tesi et al., 2011); in fact, the intertidal flat under investigation is formed by several crevasse splays (i.e. sediment fluvial deposit originated when a river breaches its levees) that develop from the breaches that connect the river channels to the Barbamarco Lagoon (Brunetta & Ciavola, 2024; Brunetta, Duo, & Ciavola, 2021). Large floods (i.e. generally higher than 6000 m³/s; Tesi et al., 2011) transport large amounts of sediment that deposit and accrete the intertidal areas of the delta. This intertidal flat development (i.e. by crevasse splay) is a typical type of restoration in river-dominated deltas, such as the case of the Mississippi Delta (Boyer, Harris, & Turner, 1997), where large episodic river diversions lead to a rapid development of intertidal to supratidal areas, consequently leading to the restoration of the coastal wetland (Day et al., 2016). The levees that limit the intertidal flat are composed of reeds (*Phragmites australis*) (Verza & Catozzo, 2015), and the only plant species observable in the middle of this flat are occasional patches of *Spartina* spp. that change location seasonally.

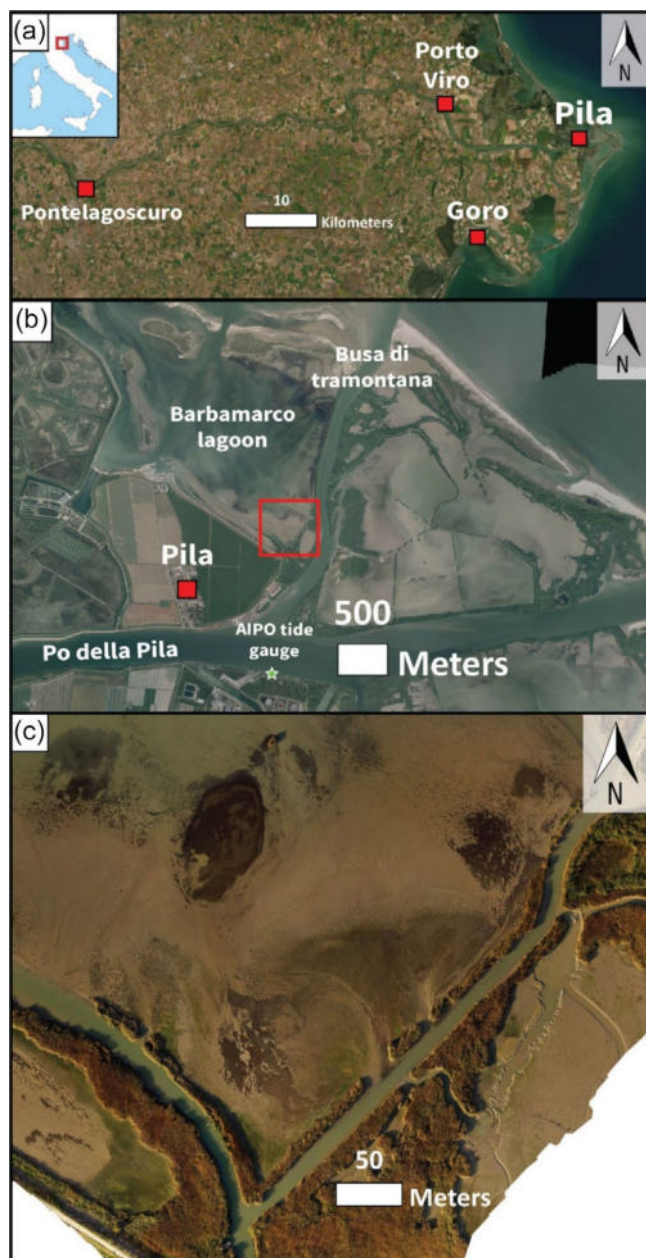


FIGURE 1 (a) The first study case is located in the Po River Delta, (b) in the southern portion of the Barbamarco Lagoon, connected to the Po della Pila branch through the Busa di Tramontana (orthophoto 1:35000 from 2015 made available by the Veneto region). The green star shows the position of the tide gauge of AIPO, which was used for the analyses. (c) The intertidal flat under investigation develops between two channels (photo achieved during the field campaign of October 2018). The sediment is brought inside this system during floods through small mouths that connects the channels and the intertidal flat, allowing the development of a crevasse splay in the middle. AIPO, Agenzia Interregionale Per il Fiume Po.

2.3 | Perkpolder (The Netherlands)

The intertidal flat of Perkpolder is part of a restoration project located in the Scheldt Estuary (province of Zeeland, The Netherlands), which aims to restore the natural wetlands and develop recreational facilities in order to prompt the socio-economic development of the area (Figure 2a,b) (van de Lageweg, 2019). This polder was initially dammed in 1210, and the land was soon reclaimed for agriculture and the construction of small villages. Over time, the land behind the dike



FIGURE 2 (a) The second study case is located in the Scheldt Estuary, in the Province of Zeeland (The Netherlands), near Walsoorden. (b) The Perkpolder intertidal flat is a 75 ha restored tidal system built after the reclamation of several agricultural fields. New dykes limit the submerged area and the northern inlet connects the water of the estuary with the basin. The green star shows the location of the tide gauge at Walsoorden used for the analyses (image available by the GeoWeb of Rijkswaterstaat – [Link](#)).

subsided, lowering it below sea level. Because of its proximity to the Schaar van Ossensisse, a deep channel in the Western Scheldt, the coastline became vulnerable to dike breaches. In 1841, a new dike about 1-km long was constructed along the coast, but half of it was soon lost. The estuary, characterised by a length of 355 km from source to mouth and a total catchment area of 22 000 km², is characterised by a tidal range that varies from about 3.8 m at Vlissingen (at the mouth) to about 5.2 m at Antwerp (78 km upstream). The study site is macrotidal with an average tidal range of 4.6 m and a mean spring tidal range of about 5 m (Claessens & Belmans, 1984).

The fine sediment of the Scheldt Estuary originates from both marine and terrestrial sources; however, the ratio between these two varies significantly. This variation is influenced by changes in the location of the Estuarine Turbidity Maximum (ETM) and fluctuations in sediment loads from the Scheldt's tributaries (Brinke, 1994; Chen et al., 2005; Swart, 1987; Wartel et al., 1993). Sediment transport rates are seasonally dependent and influenced by tidal cycles; suspended concentrations are typically higher, especially during flood tides and spring tides compared to ebb tides and neap tides. In winter, a stronger correlation is found between suspended concentration and tidal amplitude, with peak concentrations occurring one tide after the highest tide. These seasonal shifts are driven by factors such as fresh-water discharge, temperature and land erosion; wave-induced resuspension plays a smaller role (Fettweis, Sas, & Monbaliu, 1998).

The intertidal flat started its development in June 2015, after 75 ha of agricultural fields were submerged by the salt water of the Western Scheldt. The water exchange is provided by the opening of an inlet of about 300 m that connects the intertidal flat with the estuary, while two artificial creeks of about 40 m in width and a total length

of about 800 m were dug to facilitate water distribution. The location of the intertidal flat is particularly convenient from a sedimentological point of view through to its proximity to the turbidity maxima caused by the mix of strong tidal currents and riverine water masses, as well as residual currents, that increase the residence time of the suspended material (Chen et al., 2005). This restoration project can be associated with an 'active' restoration approach; more specifically, an assisted regeneration, where restoration focusses on actively triggering the natural regeneration capacity of biota (Gann et al., 2019); in this case, the trigger is the breach of the dykes and the artificial creeks, made to help the recovery of the intertidal environment.

2.4 | Converse (Bay of Fundy, Canada)

The third study site is located in the northern basin of the Bay of Fundy (East Coast of Canada), in the Tantramar Marsh system, next to the Cumberland Basin (Figure 3a,b). This large bay is characterised by wide salt marshes that have decreased by an estimated 30 500 ha

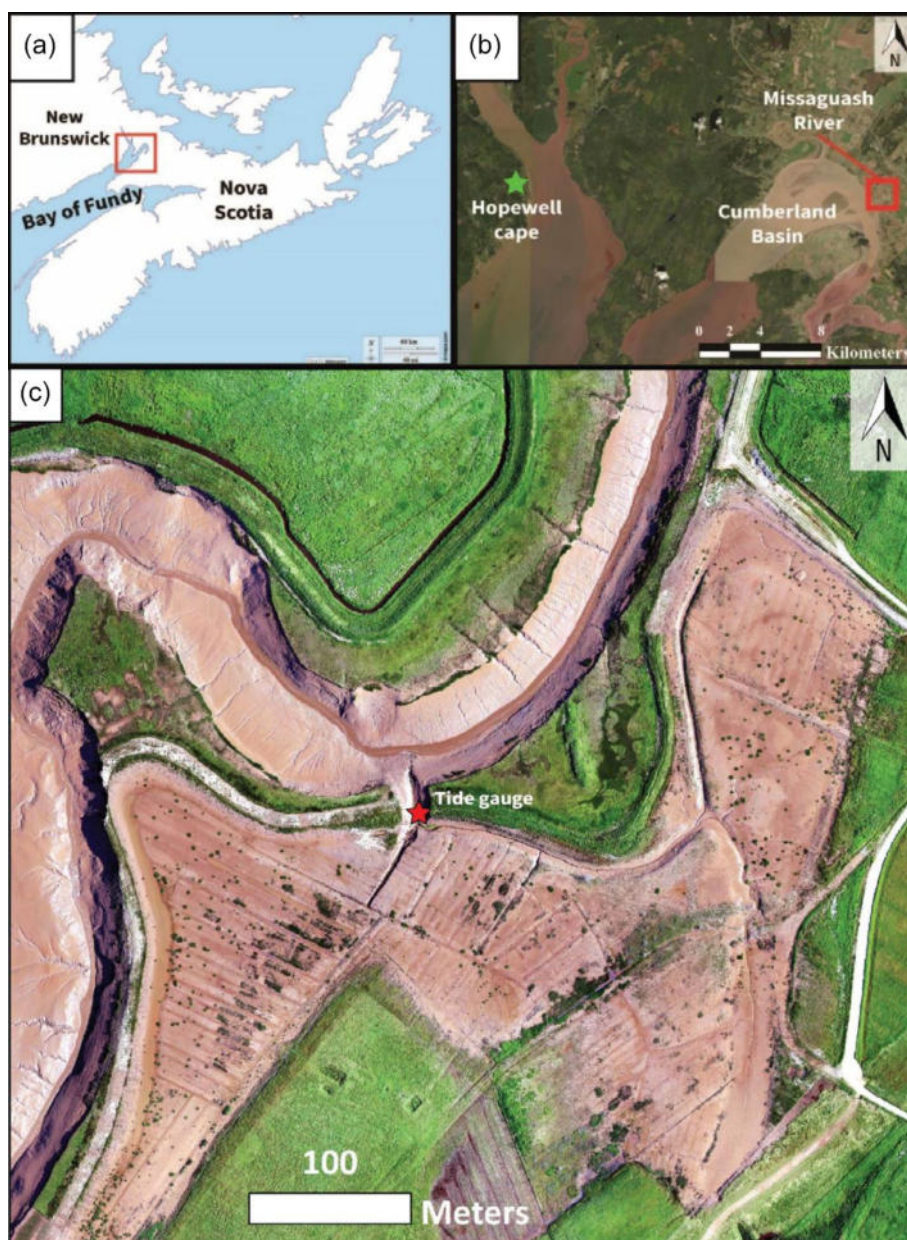


FIGURE 3 (a, b) The third study case is located in the Cumberland Basin, the eastern estuary of the Bay of Fundy. The green star shows the position of the station of Hopewell Cape, which was used to define the local mean sea level. (c) The restoration project of Converse is located along the Missaguash River, and it is a 14-ha intertidal flat formed after the reclamation of agricultural fields which are connected to the river through a small inlet located in the northern side. The red star shows the position of the tide gauge deployed during the fieldwork (photo achieved during the field campaign of July 2021). Imagery collected by S. Lewis on 25 July 2021 with a DHI Phantom 4 RTK RPAS.

(~85% of the initial area) since European colonisation in the 17th century (Thomas, 1983). The Tantramar marsh system includes a high variety of marshes, rivers and lakes that extend for about 230 ha, and it connects the provinces of New Brunswick (NB) and Nova Scotia (NS). This large wetland complex was highly reduced during the last 400 years, because of human intervention (e.g. dykes and transportation routes). The study site is located along the Missaguash River, one of the large tidal rivers that divides the two provinces (Figure 3c).

A semi-diurnal hypertidal range of about 14 m characterises this large basin of about 118 km²; the western side is generally subjected to higher sediment concentration compared to the eastern side (Amos & Tee, 1989) with an average of $\sim 0.3 \text{ g l}^{-1}$, ranging from 0.05 to 4.0 g l^{-1} , mostly composed of fine to coarse silt (Amos, Tee, & Zaitlin, 1991; van Proosdij et al., 1999). Salt marshes in the Cumberland Basin are minerogenic, with seasonal contributions of inorganic sediments (including by ice) accounting for the majority of increases in surface elevation within the tidal frame (Bowron et al., 2022; van Proosdij, Davidson-Arnott, & Ollerhead, 2006).

The *Making Room for Wetlands* Converse managed dyke realignment project was initiated by the Nova Scotia Department of Agriculture in collaboration with CB Wetlands and Environmental Specialists (CBWES) and Saint Mary's University and funded by the Government of Canada to respond to extensive erosion of the existing dyke infrastructure and to restore a fraction of intertidal wetland habitat that had been historically lost in the region. The project was funded by the Environment and Climate Change Canada's National Wetland Conservation Fund (NWCF) and Department of Fisheries and Oceans Coastal Restoration Fund. The agricultural land behind the dyke was underutilised, ditched and subsided, approximately 45 cm lower in elevation than the fringing foreshore marsh (Crowell et al., 2025). The project involved removal of the existing aboiteau to allow for one main inlet and drainage channel as well as breaching a 420 m section of dyke in two locations, levelling it to the elevation of the foreshore marsh. Prior to dyke breaching, a 150-m section of new dyke was constructed using material from a 'borrow pit', a portion of the decommissioned dyke and from an adjacent upland area (Bowron et al., 2022; Crowell et al., 2025). The first overmarsh tides entered the site on 21 December 2019, setting the stage for the restoration of 15.4 ha of intertidal wetland habitat (Figure 3c). Additional details of the re-alignment design and process are provided in Crowell et al., 2025. A comprehensive post-monitoring programme was

implemented focusing on variables critical to tracking the restoration trajectory, including hydrology, hydrodynamics, soils and sediments (including surface elevation change and carbon), vegetation, and ecomorphodynamic evolution using Remotely Piloted Aircraft System (RPAS) and GIS (Bowron et al., 2022; Crowell et al., 2025). The purpose of the monitoring programme was (i) to report the evolution of the habitat and to determine whether ecological benefits occur, (ii) to describe the impacts of the tidal flow and (iii) to define whether supplementary interventions are necessary.

This site followed an 'active' restoration process as well (Gann et al., 2019) because the approach is the same of the Perkpolder study site (i.e. dyke breach and artificial creeks). Sediment transport is typically higher during flood tides and spring tides rather than during ebb tides and neap tides (Crowell et al., 2025). The depth-averaged current speeds can exceed 1 m s^{-1} inlet channel and are typically $< 0.3 \text{ m s}^{-1}$ across the flooded area with an average depth of 0.66 m over the marsh surface at high spring tides (Burns et al., 2025a). Suspended sediment concentrations typically range between 0.08– 2.0 g l^{-1} (Burns et al., 2025b; Crowell et al., 2025).

3 | METHODOLOGY

3.1 | Fieldwork

To perform comparative analyses, highly similar field methods and data processing were applied at each site. The analyses focus on morphological datasets, sediment deposition, and tide gauge and river discharge records.

3.1.1 | Surveys carried out for morphological analyses

To assess the evolution of the surface of the intertidal flats and evaluate the volume of sediment deposited or eroded, morphological analyses were achieved via RPAS flights, Lidar, and Multi-beam to obtain DSMs (digital surface models) and orthophotos of the study sites (Table 1).

At the Barbamarco Lagoon (Po Delta) study site, four surveys were carried out between October 2018 and February 2020:

TABLE 1 Summary of the surveys and DSMs that were produced in all three study cases with the relative RMSE and threshold change detection (TCD).

Study site	Date	Type of survey	DEM resolution (m)	Area (ha)	RMSE (m)	TCD (m)	Coordinate system – datum
Barbamarco Lagoon (Italy)	October 2018	RPAS flight (Phantom 3 + professional) + RTK-GPS Trimble R8	0.1	8	0.057	0.05–0.07	WGS84/UTM zone 33 N (EPSG:32633) – Genova 1942
	February 2019				0.034		
	July 2019				0.048		
	February 2020				0.037		
Perkpolder (The Netherlands)	June 2015	Aerial lidar/multibeam	$2 \times 2/1 \times 1$	75	\	0.05/0.1/0.15	Amersfoort/RD new – NAP (Normaal Amsterdam Peil)
	April 2016						
	January 2017						
Converse (Canada)	July 2019	RPAS flight (Phantom 4 RTK) + RTK-GPS Leica GS14	0.1	14	0.03	0.05	NAD83 (CSRS) UTM zone 20 N – CGVD2013
	July 2021				0.04		

(i) October 2018, (ii) February 2019, (iii) July 2019 and (iv) February 2020. For the third study case of Converse (Bay of Fundy), two RPAS surveys were carried out in (i) July 2019 and (ii) July 2021. Both study areas were investigated via RPAS flights, maintaining the same procedure; therefore, the front and the side overlap between each photo was $\sim 70\%$, and the flight speed was $8\text{--}10\text{ m s}^{-1}$. During each survey, ground control points (GCP) and validation points were collected using a GPS-RTK throughout the intertidal flat to georeference and validate the RPAS-derived DSM products. Additional details of the surveys and methods are provided in Brunetta, Duo, and Ciavola (2021) and Crowell et al. (2025).

At the Perkpolder (Scheldt Estuary) study site, three lidar surveys performed by Rijkswaterstaat (Dutch Ministry of Infrastructure and Environment) resulted in a DSM with a $2\text{ m} \times 2\text{ m}$ resolution. The first survey was undertaken in (i) June 2015, in correspondence with the opening of the inlet; the second survey was undertaken in (ii) April 2016, and the third one in (iii) February 2017. These two DSMs covered the internal areas of the system, which can be divided into two main zones: the intertidal flat, which covers the southern part, and the pond, a deeper portion of the basin that is located in front of the inlet (Figure 2b). The morphology of the inlet and the external area of the basin were derived from multi-beam datasets obtained concurrently by Rijkswaterstaat (i.e. June 2015, April 2016 and January 2017); these multibeam DSMs have a resolution of $1 \times 1\text{ m}$.

3.1.2 | Surveys carried out for sediment deposition and laboratory analyses

In the literature, several techniques were used to measure sediment deposition. The choice mainly depends on the processes that cause deposition in the investigated area and the repeatability of the measurement; thus, each method has strengths and weaknesses (Nolte et al., 2013). Sediment traps are a common, inexpensive, and practical technique that has been frequently chosen since the 1980s (Marion, Anthony, & Trentesaux, 2009), and their design is highly variable because it depends on a large number of factors related to the study case itself, such as the amount of deposition, atmospheric precipitation, sediment re-suspension, or other disturbance factors, and also the objective of the study. The design of sediment traps can significantly influence hydrodynamics, which in turn affects sediment dynamics (Bloesch & Burns, 1980). Some researchers have used flat traps, as they lack edges and are thought to minimise interference with measurements (Pasternack & Brush, 1998; Duvall et al., 2019). However, these traps are prone to content loss because of water movement from rainfall or tidal currents and are susceptible to accidental loss during retrieval (Gardner, 1980; Kozerski and Leuschner, 1999). Another common approach is the use of filter papers placed on intertidal flats or salt marsh surfaces for short or extended periods (Brown, 1998; Culberson, Foin, & Collins, 2004; French et al., 1995; Leonard, 1997; Leonard, Hine, & Luther, 1995; Neumeier & Ciavola, 2004; Price, 2016; Reed, 1989; van Proosdij, Davidson-Arnott, & Ollerhead, 2006), or plastic cylinders (e.g. centrifuge tubes; Baranes et al., 2022), which are affordable and often used for longer deployments. It is essential to consider the height-to-diameter ratio, especially in turbulent environments, to ensure accurate sampling (Bloesch & Burns, 1980). Short traps are more appropriate for calm

settings like lakes, while longer tubes perform better in more turbulent waters. The solution that was chosen for this study, thus the best compromise for these three case studies, was a sterile Polystyrene Petri dish with an edge of 1 cm and a diameter of 4.7 cm for the Barbamarco study site, while an edge of 1.5 cm and a diameter of 10 cm for the Perkpolder and Converse study cases, produced by Merck KGaA (Darmstadt, Germany). This type of trap can be considered a combination of cylinder and flat traps, and it was used in previous research because of its affordability (Butzeck et al., 2015; Temmerman et al., 2003). This choice was made to provide a flat surface that would represent the mudflat accurately while also preventing sediment loss during collection.

At the Barbamarco Lagoon study site, three sets of measurements were carried out between September 2019 and March 2021: (i) from 17 to 27 September 2019; (ii) from 26 June to 10 July 2020; and (iii) from 12 to 25 March 2021. At the Converse study site (CA), sediment traps were deployed between 23 and 26 July 2021. Three traps spaced by 60 cm and oriented in the same direction were placed in several stations, which number depends on the study site (see Table 2 and Figure 4a,c). The centre of the three vertices represents the location and the elevation of the traps of the station, and it was measured with GPS-RTK. The traps were left in the field depending on the expected rate of sedimentation. In the Barbamarco Lagoon, the traps were deployed during spring-neap tidal cycles. Because of the expected low rate of sedimentation, the traps were left in the field for several days.

Because sedimentation in the Bay of Fundy is extremely high (i.e. high risk of overfilling), the traps at the Converse site were left in the intertidal flat for a total of four tide events. In the case of stations located within areas with high deposition (RS1, RS2 and RS3), one trap from these stations was collected and replaced with a new trap after each tide, in order to measure the deposition of the single tides; the other two traps were left for the whole four tides. Where deposition was lower, depending on the amount of sediment collected, the traps were left for the whole period or the first tide was collected separately to the following three.

At the Perkpolder study site, sediment traps were deployed within two time intervals in May and June 2017: (i) from 15 May to 16 June 2017 and (ii) from 13 to 27 June 2017. Traps were located along four cross-sections during two spring-neap tidal cycles (Figure 4b). Eighteen traps were recollected during the first survey, while 39 during the second one, for a total of 57 traps out of 80 deployed.

All samples were treated, dried and weighted (see Table 2 for details). Detailed information about the trap models and treatment can be found in Brunetta, Duo and Ciavola (2025).

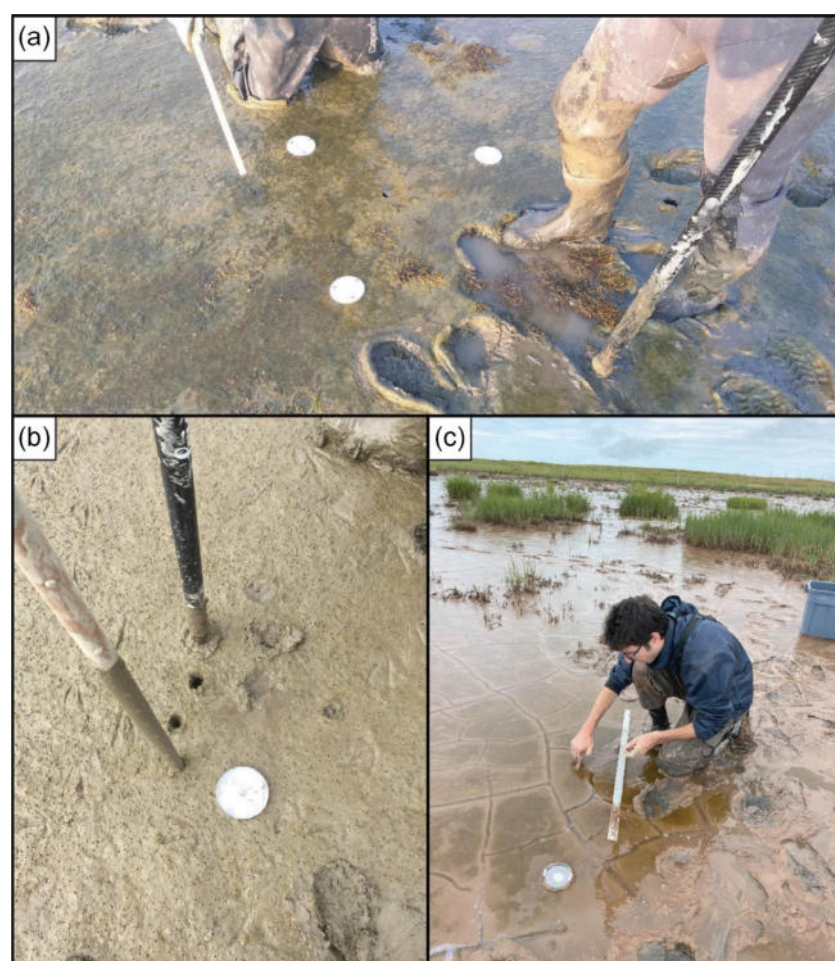
3.2 | Digital surface models analyses

3.2.1 | Pre-processing: validation of the DSMs

For the study sites of Barbamarco and Converse, the georeferenced DSMs and orthophotos were produced through the 'Agisoft Metashape' software (version 1.8.4) following the well-established Structure-from-Motion (SfM) photogrammetric technique (e.g. Fonstad et al., 2013; Casella et al. 2016, 2020; Gindraux,

TABLE 2 Summary of the surveys for sediment deposition that was carried out in all three study cases.

Study site	Date	Number of traps	Type of traps	Numbers of tide	GPS-RTK used	Sediment treatment	Coordinate system - datum
Barbamarco Lagoon (Italy)	From 17 to 27 September 2019	27 per each station (total of 81)	Petri dish with an edge of 1 cm and a diameter of 4.7 cm	9–16	Trimble R8 – TSC3	Hydrogen peroxide (30%), dried at 105°C	WGS84/UTM zone 33 N (EPSG:32633) - Genova 1942
	From 26 June to 10 July 2020			12–24			
	From 12 to 25 March 2021			13–24			
Perkpolder (The Netherlands)	From 15 May to 16 June 2017	40 per each survey (a total of 80)	Petri dish with an edge of 1.5 cm and a diameter of 10 cm.	59–63	Leica Viva GNSS GS08	Dried at 80° C and weighed	Amersfoort/RD new – NAP (Normaal Amsterdam Peil)
	From 13 to 27 June 2017			19–28			
Converse (Canada)	Between 23 and 26 July 2021	A total of 59 traps for 14 stations		1–4	Leica GS14 – CS20	Hydrogen peroxide (30%), hot plates set at 60°C to accelerate the process, dried at 70°C and weighed	NAD83 (CSRS) UTM zone 20 N - CGVD2013 rectified with the Chart Datum and the mean sea level of Hopewell Cape (45°50'26.0"N 64°33'26.0"W; Figure 3c).

**FIGURE 4** Traps positioning on the surface of (a) the intertidal flat of the Barbamarco Lagoon in the Po Delta (Italy), (b) the intertidal flat of Perkpolder (The Netherlands) and (c) the intertidal flat of Converse, in Nova Scotia (Canada).

Boesch, & Farinotti, 2017). All DSM products were cropped, removing the portions outside the domain of the GCPs and the portion characterised by signal noise derived from water. For consistency, the DSMs were exported at a resolution of 0.1 m and cropped in order to

perform the analysis exclusively on the same area. The validation points measured during the surveys allowed for an estimate of the RMSE (root mean square error) of each model, which evaluates the average accuracy of the products. In the case of Perkpolder,

because the DSMs are lidar- and multibeam-derived and no validation or point cloud were available, an evaluation of the reliability of the products with on-field data was not feasible. Therefore, a different approach was carried out (see Perkpolder study case for more details).

3.2.2 | Pre-processing: variations within the study cases

The managed realignments (i.e. Perkpolder and Converse) presented highly different vertical changes across the study sites that demanded a segmentation of the areas, separating the intertidal flats from the breaches and the external domains of the systems in order to distinguish the focus of accretion and erosion. The following sections describe how the DSMs were divided and analysed to evaluate the sediment budget and the vertical variations.

Perkpolder study case

To understand the morphological evolution of the intertidal flat, the breach and the external portion of the system of Perkpolder, the study area was divided into four zones, similar to the method applied in van de Lageweg et al. (2019), based on the morphological characteristics (e.g. morphological forms, main changes and location) (Figure 5): (i) Zone 1 – the proper intertidal flat (Middle Flat) located in the southern part, (ii) Zone 2 – the pond, which is an area located on the western side of the inlet, mainly ranging from the Lower Flat to the Subtidal (Amos, 1995), (iii) Zone 3 – the area located nearby the breach, and (iv) Zone 4 – which comprises the nearby areas of the breach and the eastern external part. Based on the data available and the most relevant morphological changes, the time intervals chosen are: (i) from June 2015 to April 2016, (ii) from April 2016 to February 2017 and (iii) from June 2015 to February 2017.

Converse study case

In the case of Converse, the intertidal flat included patches of vegetation, such as bushes present before the opening of the breach that subsequently died with the introduction of saline water and patches of vegetation that grew in the following years that needed to be removed from the DSMs to achieve a reliable evaluation of the vertical and volumetric changes. Therefore, the DSMs of 2019 and 2021 were cropped using image classification techniques combined with manual editing based on the orthophotos (see Crowell et al., 2025 for more detail). All the gaps derived from this pre-processing were filled using the QGIS tool 'Fill Nodata'. However, the gaps derived from large water ponds or large patches were left blank, because wide holes of data filled with this tool may cause artifacts. As for the study case of Perkpolder, the domain was segmented based on the morphological characteristics and evolution (Figure 6). Three main areas were selected for the analysis: (i) Zone 1 – the intertidal flat itself (Higher Flats), (ii) Zone 2 – the inlet area with the internal channels (Higher to Middle Flats) and (iii) Zone 3 – the external area of the meander of the tidal channel. These areas were cropped in order to separately measure the volumes and the vertical changes. The limit between the intertidal flat and the inlet/internal channels was defined by the steep angle that separated the two morphologies. The external area was chosen based on the reliability of the DSMs area (i.e. removing noises related to water, etc).

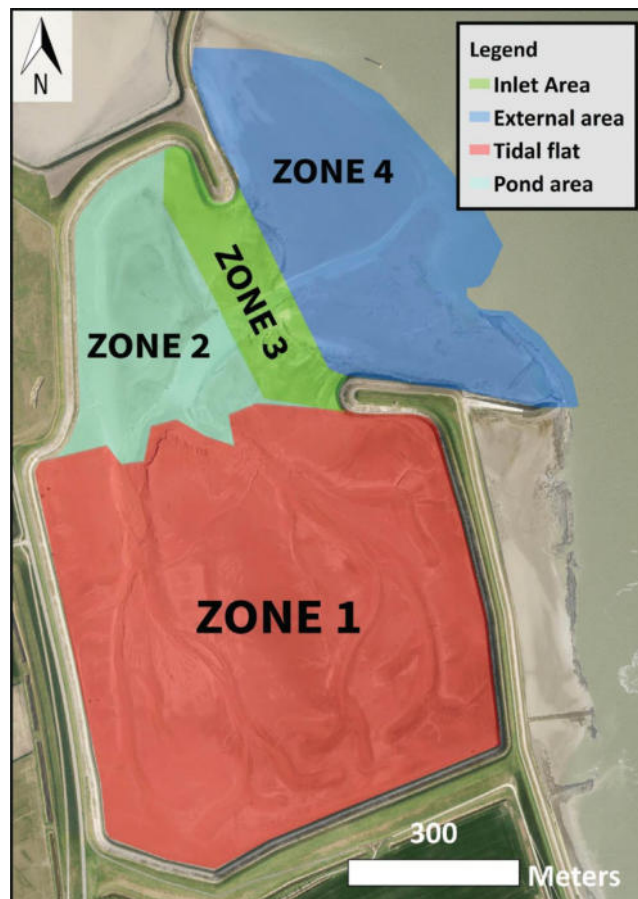


FIGURE 5 Portions of the study area of Perkpolder (NL) that were cropped and analysed separately. Zone 1 represents the proper intertidal flat (middle flat); Zone 2 represents the pond, a depressed area between the lower flats and the subtidal range, located next to the inlet; Zone 3 includes the area nearby the inlet; Zone 4 is the area external to the breach.

3.2.3 | DEM of difference (DoD): analyses and significance of the vertical changes

The rate of vertical changes and the volumetric changes were evaluated across all datasets from all study areas using the Geomorphic Change Detection (GCD) tool of Wheaton et al. (2010). This tool performs an analysis of vertical variations and volume gain and loss, providing an uncertainty assessment based on a given threshold for change detection (TCD); variations falling below this threshold are not deemed significant and ignored, focussing on the most substantial changes. The GCD tool accounts for individual errors relative to each DSMs when performing a Differential DEM (DoD) analysis. They can be propagated as shown in Equation (1):

$$\delta_{\text{DoD}} = \sqrt{(\delta_{\text{zNew}})^2 + (\delta_{\text{zOld}})^2} \quad (1)$$

where δ_{DoD} is the propagated error, while δ_{zNew} and δ_{zOld} are the individual errors of each DSM. The propagated error was considered as the uniform TCD. Previous studies defined the TCD considering statistical coefficients, such as the *t*-value (Lane, Westaway, & Hicks, 2003; Milan, Heritage, & Hetherington, 2007; Wheaton et al., 2010), thus attributing a level of significance. In the present

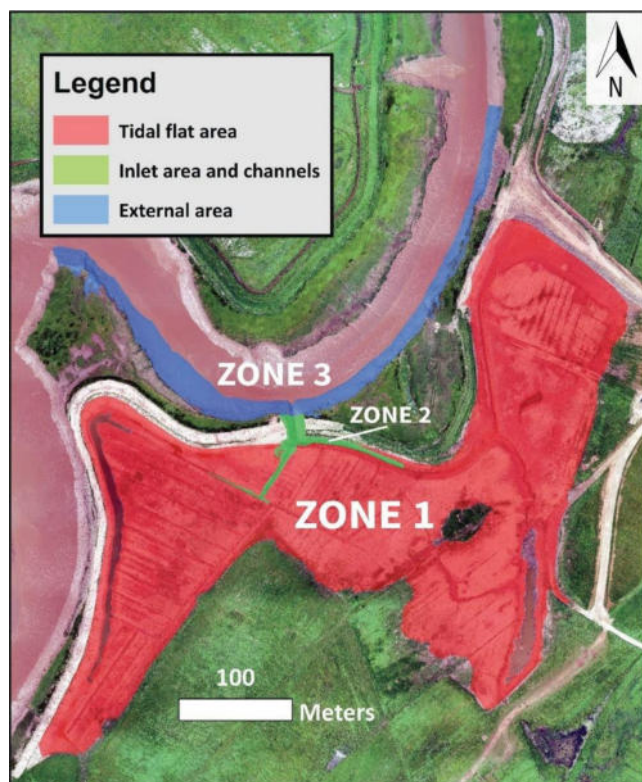


FIGURE 6 Portions of the study area of Converse (CA) that were cropped and analysed separately. Zone 1 represents the intertidal flat (higher flat), after filtering vegetation and avoiding large ponds; Zone 2 includes the area nearby the inlet and the nearby deep channels (higher to middle flat); Zone 3 is the area external to the breach.

study, given the characteristics of the study areas and the magnitude of morphological variations, a t -value of 1 was applied. This corresponds to a significance level of 68%. Although a t -value of 1.96 corresponds to a significance level of 95%, hence a higher confidence in the results, increasing the TCD to evaluate morphological changes in tidal environments can entail a substantial loss of data. The GCD tool provides information regarding the areal, volumetric and vertical changes (i.e. total and net variations, raising and lowering surfaces, area subjected to these variations and the entire study area) with relative uncertainties.

Perkpolder study case

As previously mentioned, for the study case of Perkpolder, the DSMs are lidar- and multibeam-derived and no error estimation was feasible. Commonly, lidar-derived DSMs in intertidal coastal environments are influenced by vegetation, maintaining accuracy generally between 0.1 and 0.45 m (Millard et al., 2013; Morris et al., 2005; Rosso, Ustin, & Hastings, 2006; Schmid, Hadley, & Wijekoon, 2011; Wang et al., 2009). In the case of Perkpolder, the study area was completely un-vegetated and no large bed features were present; therefore, it was considered unnecessary to further re-process the DSMs. Fernandez-Nunez, Burningham and Ojeda Zujar (2017) show that mudflats in lidar surveys are represented with very high accuracy (0.04–0.09 m), and the effects of corrections in this kind of environment can be meaningless or even increase the error. Because it was not possible to provide an accuracy assessment, a range of the individual error was taken into account considering this type of environment (0.04–0.09 m), leading to an error

estimation between 0.06 and 0.12 m. The vertical and volumetric changes were made considering thresholds of 0.05, 0.10, 0.15 m and no threshold at all (e.g. Duo et al., 2021).

Similar considerations were carried out for the multibeam-derived DSMs. The accuracy of a multibeam bathymetric DTM is related to several factors, such as survey equipment and procedures; speed; roll; pitch; heave of the vessel; the height of the water column, water level and flows; and a large number of other factors that depend on environmental and sea conditions (salinity, etc). While specific error ranges can differ based on the previous factors, general trends have been documented in hydrographic literature. The International Hydrographic Organisation (IHO) Standards for Hydrographic Surveys (2020) states that the error is generally low in shallow waters (< 10 m) with respect to deeper waters. Following the IHO standards, Ernsten et al. (2006) evaluated the vertical accuracy of bathymetric surveys in shallow waters, identifying an average vertical error from ± 0.02 to ± 0.08 m at a 95% confidence level. Elias et al. (2023) also estimated the accuracy in the Westerschelde at different depths, finding an average range of ± 0.1 m. Therefore, the thresholds used for the DoD of the multibeam-derived DTMs were the same (i.e. 0.05, 0.10, 0.15 m and no threshold at all).

3.3 | Sedimentation rates

Sediment deposition rates can be calculated following different approaches depending on the purpose of the study and the inundation events. A typical representation considers the daily rate in grams per square meter per day (g m^{-2} per day) (e.g. Brown, 1998; Butzeck et al., 2015; Culberson, Foin, & Collins, 2004), although it is not accurate because the tidal oscillation do not always occur at the same time of the day. Other authors prefer to use the tide event-based rate, measured in grams per square meter per tide event (g m^{-2} per tide event) as Leonard, Hine, and Luther (1995) and van Proosdij, Davidson-Arnott, and Ollerhead (2006) did, or in grams per square meter per Spring–Neap tide event (e.g. Temmerman et al., 2003). In certain cases, when deposition is highly low, the rate can be calculated considering the whole year (g m^{-2} per year) (Pasternack & Brush, 1998).

In this paper, under the assumption that deposition is constant in time, it was chosen to estimate the sediment deposition rate (S) using the following Equation (2) for all study cases:

$$S = \frac{w}{(\pi r^2) \cdot t} \quad (2)$$

where w is the average weight of sediment collected by the three traps of the station (see Section 3.2.2), r is the ray of the Petri dish, and t is the tide event. In this study, the ‘tide event’ represents the ‘inundation event’, therefore how many times the trap was submerged by the tide during a given period, which depends on the study case.

3.4 | Tide gauge and river discharge dataset integration

The analyses carried out in each study area were integrated with tide gauge and river discharge records to give a better context and obtain

a wider understanding of the evolution of these intertidal flats. All data were referred to the same datum mentioned in the previous paragraphs for consistency. The tide gauge data of each study area were used to calculate the average inundation period of each trap, computing the time interval when the tidal elevation exceeded the elevation of the bed where the trap was located.

In the case of the Barbamarco Lagoon, because the influence of the river is fundamental for the development of the intertidal flat under investigation, the dataset of the river discharge was provided by the station of Pontelagoscuro of ARPAE (Agenzia Regionale per la Portezione Ambientale Emilia-Romagna) (44° 53' 17.9" N 11° 36' 29.1" E; Figure 1a), while the tidal variations were obtained through the station of Pila provided by AIPO (Agenzia Interregionale Per il Fiume Po), which has a sampling period of 30 min (44° 57' 41.0" N 12° 29' 34.0" E; Figure 1b);

The tidal records regarding the study area of Perkpolder were provided by the station of Walsoorden operated by Rijkswaterstaat, which has a sampling period of 10 min (51° 23' 55" N 4° 01' 36.8" E; Figure 2a);

For the Converse site, a Nortek Aquadop acoustic Doppler current profiler (ADCP), used as a pressure transducer, was located and fixed on the surface of the central part of the inlet that connects the river to the intertidal flat. The tool measured the water level variations for the whole survey (from 23 to 26 July 2021, sampling period of 10 s). The location of the sensor was measured with the GPS as well, and the offset was considered in the correction. The vertical datum is CGVD2013, which is the most recent Canadian standard. As mentioned in Table 2, the vertical datum is corrected with the Chart Datum and the mean sea level of Hopewell Cape (Figure 3c).

4 | RESULTS

4.1 | Rates of deposition of young intertidal flats

Average rates of deposition and associated trends are presented for each case study, describing first the results found in the Barbamarco Lagoon, in the basin of Perkpolder and then in Converse. Finally, all datasets are combined and compared. Details including datasets and calculations are provided in Appendix A.

4.1.1 | Barbamarco Lagoon (Po Delta)

The intertidal flat of the Barbamarco Lagoon experienced variable rates deposition depending on the seasonality. During the autumn–winter seasons, a rate of about 20.7 g m⁻² per tide event (Figure 7a) was recorded, which is a similar rate found during the spring season as well, with values of 18.9 g m⁻² per tide event (Figure 7c). Higher values are found during the summer season, reaching 66.8 g m⁻² per tide event (Figure 7b). The average between all the traps from all the surveys carried out in the lagoon showed a total average sedimentation of 36.7 g m⁻² per tide event; the average inundation period for all traps varied from 3.67 to 25 h. In all surveys, sedimentation increases from the most elevated areas to the lowest elevations; no strong influence caused by other morphological structures (i.e. channels and inlets) was observed. The tables that summarise all

the sediment collected by the traps during the surveys in the Po Delta and the relative calculations can be found in Tables A1–A3. Details regarding the error estimations are reported in Brunetta, Duo and Ciavola (2025).

4.1.2 | Perkpolder (The Netherlands)

Although a few rates of the Po Delta may reach comparable values with the intertidal flat of Perkpolder (i.e. around 230 g m⁻² per tide event), the macrotidal flat is subjected to higher average sedimentation of 64.1 g m⁻² per tide event. The rates calculated for both surveys were highly comparable, showing 59.1 g m⁻² per tide event collected during the first survey (Figure 8a) and 66.4 g m⁻² per tide event during the second survey (Figure 8b). It is important to note that these rates of deposition presented a high range of values from 2.4 to 265.5 g m⁻² per tide event with a hydroperiod between 4 and 10 h (Figure 8c). Deposition was higher inside and next to the creeks; in particular, it increased as the distance from the inlet increased, it decreased as the distance from the creeks increased, and as elevation increased. All the sediment collected by the traps and the relative calculations can be found in Tables A4 and A5.

4.1.3 | Converse (Canada)

The highest range of deposition was found in the study site of Converse (i.e. Bay of Fundy, Canada), which experienced average rates of 154.3 g m⁻² per tide event after 1 and 3 h of inundation (Figure 9a,b). In this case, the rates were highly influenced by the changes in elevation. In fact, a wide range of value was measured, from 1.33 g m⁻² per tide event on the most elevated areas of the flat to 726.5 g m⁻² per tide event in the lowest portion located in the northeastern part of the study area (Figure 9a). All the sediment collected by the traps and the relative calculations can be found in Table A6. It is interesting to note that the sum of the sediment weight collected during the single tide events (of a single station) is comparable with the traps that were submerged by the whole four tide events (i.e. average 0.8 g of standard deviation).

4.1.4 | Average inundation versus average deposition

The average rates of deposition are compared with the inundation period of the surveys of the study sites in Figure 10a. As expected from the literature (e.g. Temmerman et al., 2003), an exponential relationship is found in all study cases, which is also statistically significant (markedly lower than $p < 0.01$ for all cases). However, the Pearson R -value is highly variable depending on the site (from 0.9 for Converse to 0.4 for Perkpolder). The Converse study case shows the highest correlation between the sediment deposition and inundation; however, in the case of Perkpolder, data are scattered and there is a low correlation. The rates found in the Po Delta show a good exponential relationship as well; however, the correlation improves if rates calculated from one single survey (i.e. only from September or July, or March) are chosen (Figure 10b).

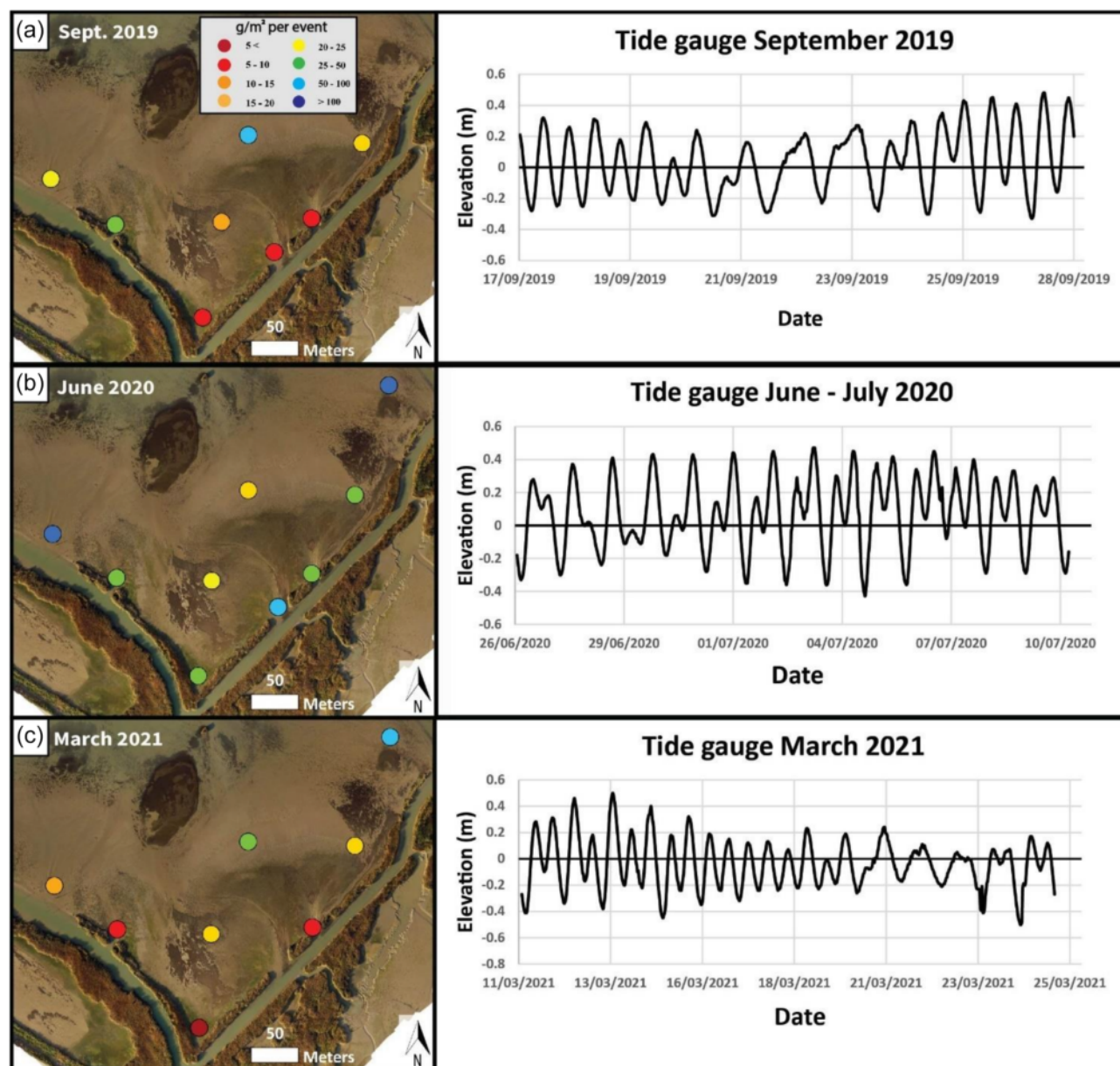


FIGURE 7 Rates of deposition obtained in the intertidal flat of the Barbamarco Lagoon during (a) September 2019, (b) June–July 2020, and (c) March 2021 and their relative tidal records provided by AIPO. AIPO, Agenzia Interregionale Per il Fiume Po.

4.2 | Sediment budget, vertical changes and breach evolution

In the following paragraph are presented the results obtained from the DoDs analyses, which allow to estimate volumes and vertical variations of each intertidal flat under investigation. The analyses describe in order the evolution of the intertidal flat of the Barbamarco Lagoon, Perkpolder and Converse. The managed realignments include more information regarding the different portions of the flats and the breaches.

4.2.1 | Barbamarco Lagoon (Po Delta)

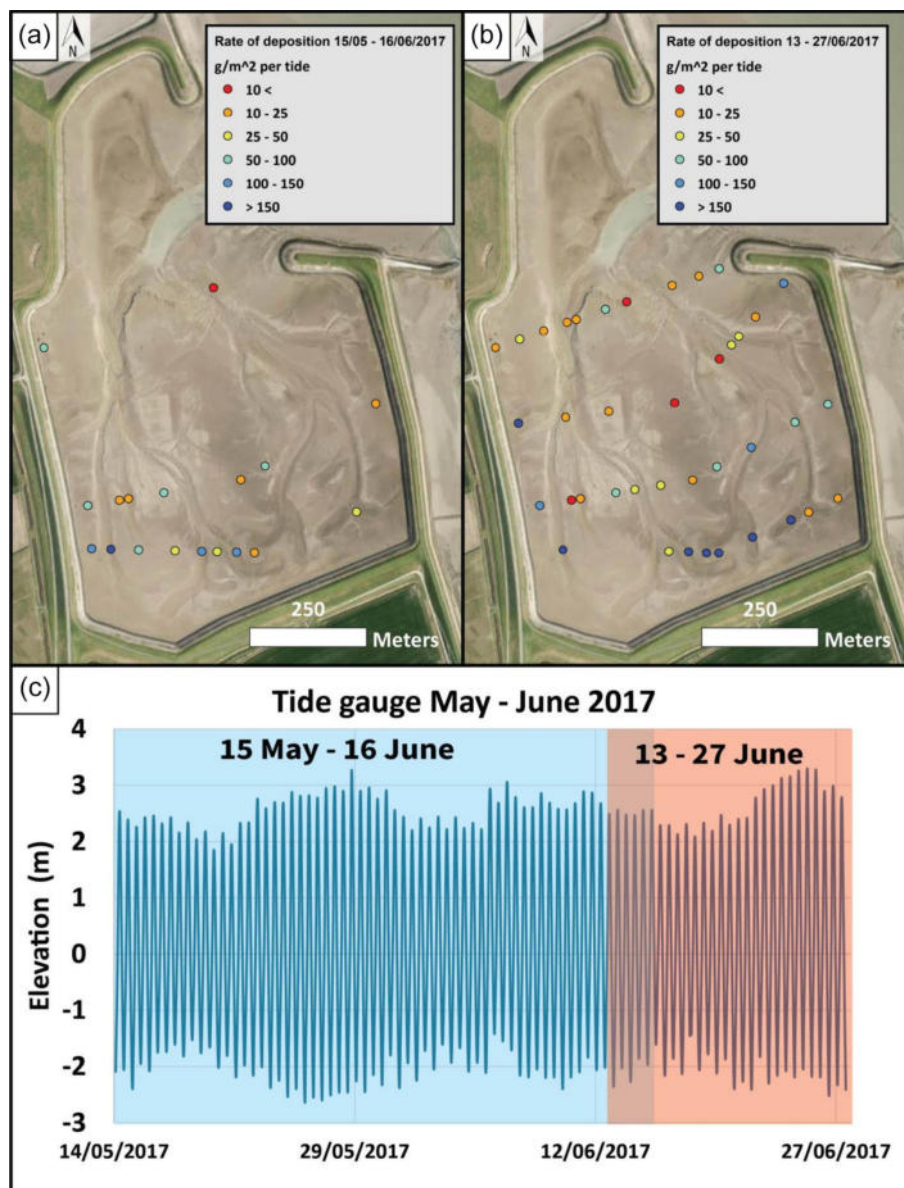
Rates of vertical change in surface elevation exhibited similar seasonal variability as deposition rates previously reported. (Brunetta, Duo, & Ciavola, 2021, 2025). The rates varied from $\sim -2 \text{ cm a}^{-1}$ (i.e. erosion) during spring–summer, to $+4.8 \text{ cm a}^{-1}$ after the flood of November

2019; however, the average rate of vertical changes is 1.3 cm a^{-1} (Figure 11). The study area has a positive sediment budget; between October 2018 and July 2019, the intertidal flat maintained a relatively stable condition characterised by an erosion of 400 m^3 . Between July 2019 and February 2020, strong floods occurred and an average of 1300 m^3 were deposited. During the whole study period, the sediment budget was about 800 m^3 per year. Most of the deposition occur in the northern part of the intertidal flat, which is the lowest portion of the study area, while the western portion is subjected to erosion. For detailed description of the seasonal variations and the relation with the river floods, refer to Brunetta, Duo and Ciavola (2021, 2025).

4.2.2 | Perkpolder (The Netherlands)

The Perkpolder site was characterised by a wide range of rates of vertical changes. The overall average accretion during the first year after its opening was about 6 cm a^{-1} , and it slightly decreased to 5 cm a^{-1}

FIGURE 8 Rates of deposition for the case study of Perkpolder for (a) the period between 15 May and 16 June 2017, and (b) between 13 and 27 June 2017. (c) The tidal level variation during the surveys.



during the second year. However, the most elevated areas (i.e. 0.5 m above m.s.l.) were characterised by lower rates of about 3.2 and 2.6 cm a⁻¹. Erosional trends were visible in the areas near the inlet; strong erosion affected the area, enlarging and deepening the channels and the inlet itself, which after 8 months reached an equilibrium state (Brunetta, de Paiva, & Ciavola, 2019). However, the internal areas were subjected to strong accretion, in particular inside the creeks, where the rates of vertical changes reached a maximum of 130 cm in 20 months.

As shown in Figures 12 and 13, the volume variations of the whole restoration project for all periods show clear trends, in spite of which TCD was chosen. Here, the results with a TCD of 0.1 m are presented (Table 3); for more detail, see Tables A7–A9.

During the first period between June 2015 and April 2016, a net sediment budget of about 61 000 m³ was deposited inside the system; most of the budget was located inside the pond (Zone 2), with a net sediment of about 44 000 ± 7319 m³, and the rest of the budget (about 17 000 ± 13 000 m³) was located inside the intertidal flat (Zone 1) (Figure 12a). In the same period, the inlet area (Zone 3) lost a net

volume of about 2200 ± 1400 m³ (~4200 ± 1200 m³ considering the total surface lowering); the inlet and the whole portion in front of the inlet are the areas that eroded the most (Zone 4) and were characterised by a sediment loss of about 22 000 ± 8000 m³ (~25 000 ± 8000 m³ considering the total surface lowering) (Figure 13a).

A similar trend was found during the following period (i.e. April 2016 to February 2017), where the sediment budget was still positive but decreased to 15 000 m³. Most of the sediment deposited inside the pond (Zone 2) reaching 9000 ± 4800 m³; the intertidal flat (Zone 1) instead collected m³ (Figure 12b). The inlet underwent erosion once again keeping very similar volumes; the inlet itself (Zone 3) lost the same sediment budget (3200 ± 1400 m³), while the whole external area lost 11500 ± 7400 m³ (Figure 13b).

Overall, the system recorded a net positive sediment budget of about 88500 m³, where 35 000 ± 19000 m³ was deposited inside the actual intertidal flat (Zone 1), and 53 500 ± 7200 m³ inside the pond (Zone 2) (Figure 12c). The inlet (Zone 3) lost about 5600 ± 2100 m³, while the external area was subject to a constant strong erosion that caused a sediment loss of about 36 500 ± 11 200 m³ (Figure 13c).

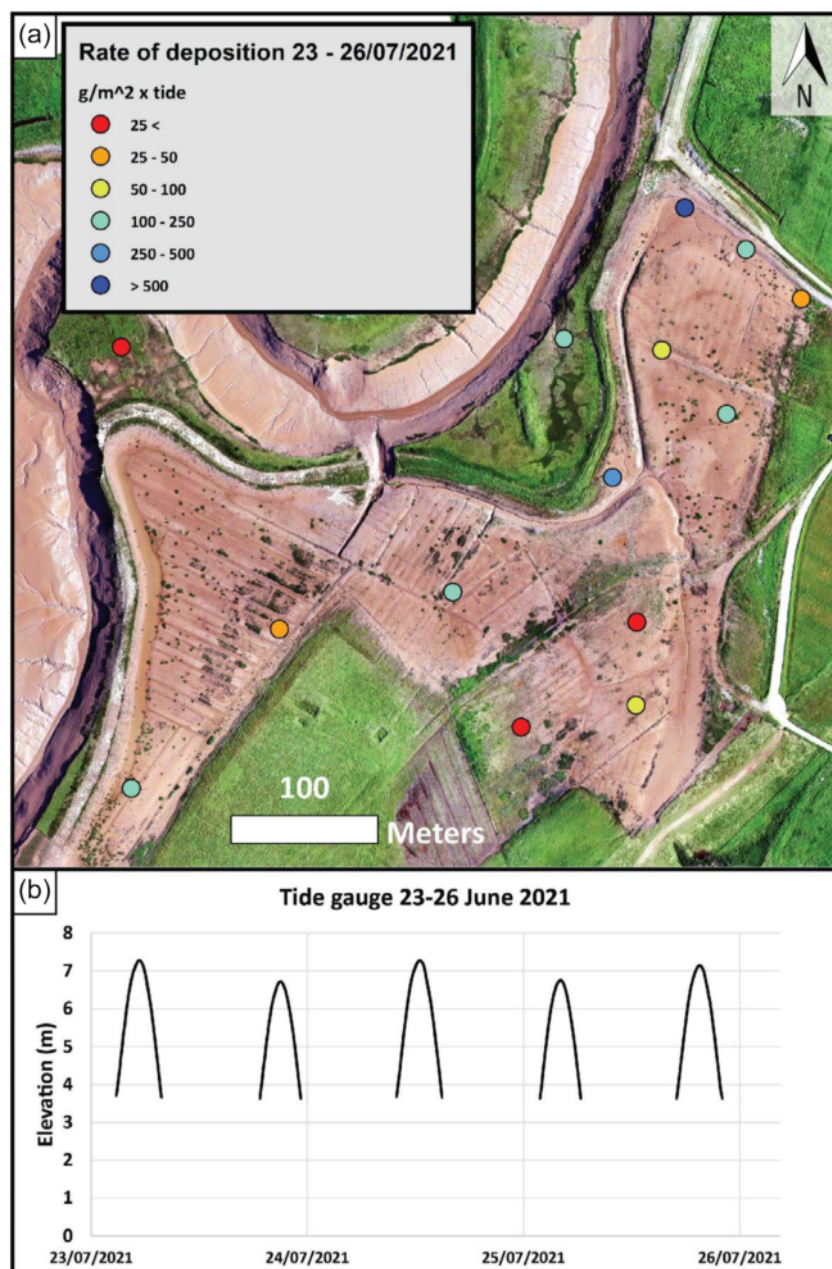


FIGURE 9 (a) Rates of deposition per tide event for the case study of Converse between 23 and 26 July 2021, and (b) the tidal level variation obtained from the ADCP during the fieldwork (the intertidal flat (higher flat) ranges between 5.5 and 6.5 m above m.s.l.). ADCP, acoustic Doppler current profiler.

4.2.3 | Converse (Canada)

If the overall rates of vertical changes of the Converse intertidal flat are considered, it seems like the system is stable and not collecting sediment (i.e. $\sim 0 \text{ cm a}^{-1}$); however, the vertical changes are highly discontinuous along the intertidal flat. The most depressed areas on the eastern portion of the intertidal flat were characterised by high rates of accretion higher than 10 cm a^{-1} , especially at the end of the creeks (Figure 14). Instead, the central-western areas did not undergo marked deposition, and the central portion of the flat experienced erosion higher than 5 cm a^{-1} , which might result from the collapse of air pockets formed during the the initial burial of pasture grasses (Crowell et al., 2025). Erosion increases moving to the inlet area; in particular, the inlet itself is enlarging at a rate of 1 m a^{-1} and has not found a morphodynamic equilibrium after 2 years. The external part of the meander that connects the intertidal flat to the river

mainly experienced erosion, although the western side to the inlet accumulated a large sediment lens higher than 0.5 m during the study period.

The study case of Converse experienced an overall net gain of about 200 m^3 during the study period (Table 4). However, the distribution of the sediment accumulation and erosion clearly focusses on a specific portion of the intertidal flat, as mentioned in the previous paragraphs. The eastern area, and partially the western area of the intertidal flat, accumulated about $1500\text{--}2000 \text{ m}^3$, while the central area lost $1300\text{--}1900 \text{ m}^3$. The most noticeable erosion extends to the internal channels located next to the inlet and the inlet itself, where a loss of about 650 m^3 occurred. Considering the external part of the creek that connects the intertidal flat to the basin, the erosion reaches about 2500 m^3 , although a hotspot of deposition occurred on the external western side of the inlet, with an accumulation of about 1600 m^3 .

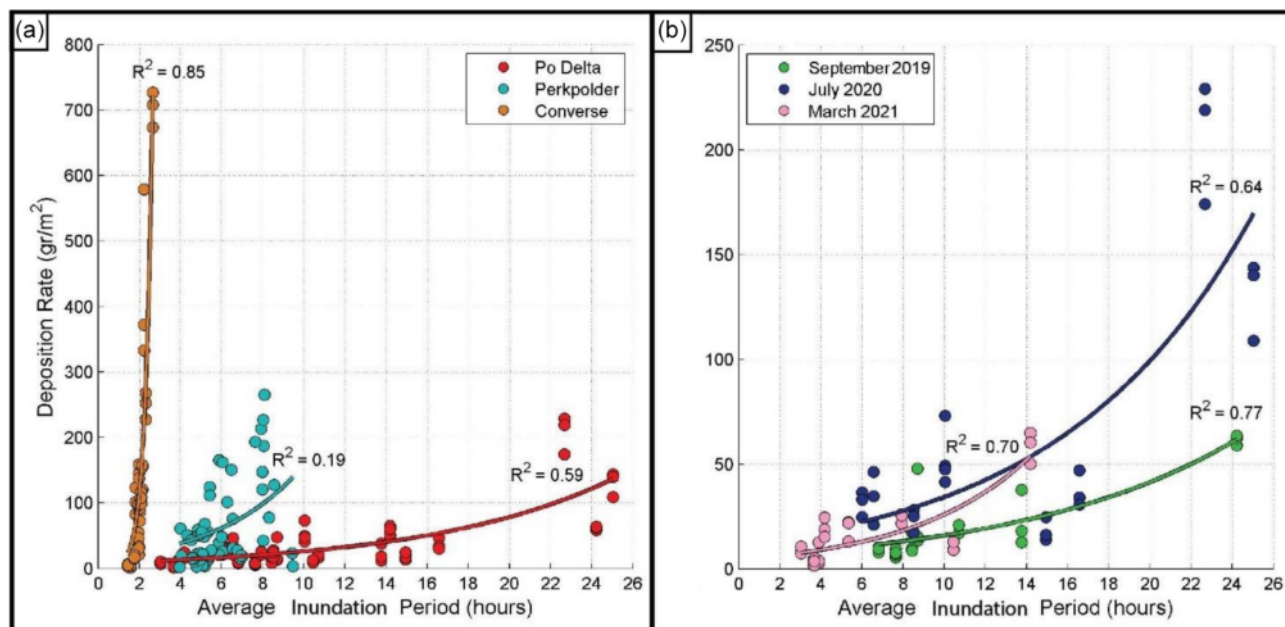
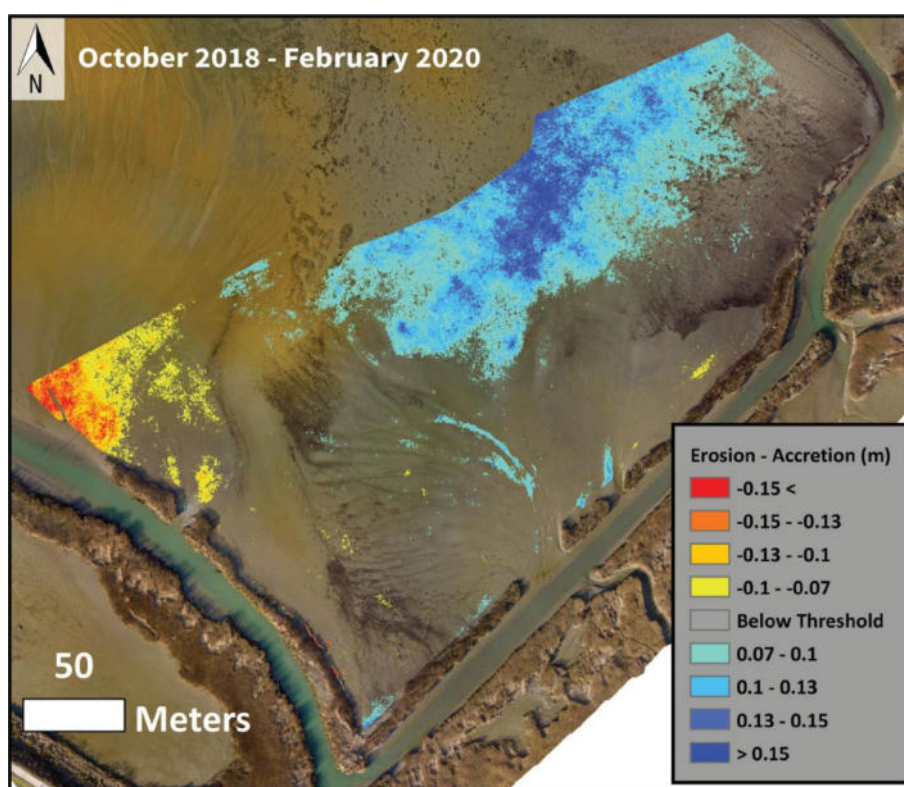


FIGURE 10 (a) Rates of deposition compared to the average hours of inundation calculated from all traps of all surveys from the Po Delta (IT), Perkpolder (NL) and Converse (CA). (b) Rates of deposition of the three surveys carried out in the Po Delta during different seasons.

FIGURE 11 Rates of changes from October 2018 to February 2020 of the intertidal flat of the Barbamarco Lagoon.



5 | DISCUSSION

5.1 | Factors that control sediment deposition in restored intertidal flats

5.1.1 | Variability of the rates of deposition in intertidal flats

Despite the provenance of sediment, tidal currents affect the distribution of the sediment supply, although their influence on deposition

highly depends on site-specific characteristics. For example, sediment transport in microtidal environments (i.e. Mediterranean Deltas) is mostly controlled by the river (e.g. Hensel, Day, & Pont, 1999; Ibáñez et al., 2010), and tidal currents commonly do not introduce sediment inside the system but do redistribute the material brought by the river, such as in the case of the Po Delta (Brunetta, Duo, & Ciavola, 2021), or storms, such as in the case of the Venice lagoon (Ciavola et al., 2002). For the intertidal flat of the Barbamarco lagoon (i.e. Po Delta), high deposition and vertical variations occur during strong floods, which means that the rates of vertical changes are not

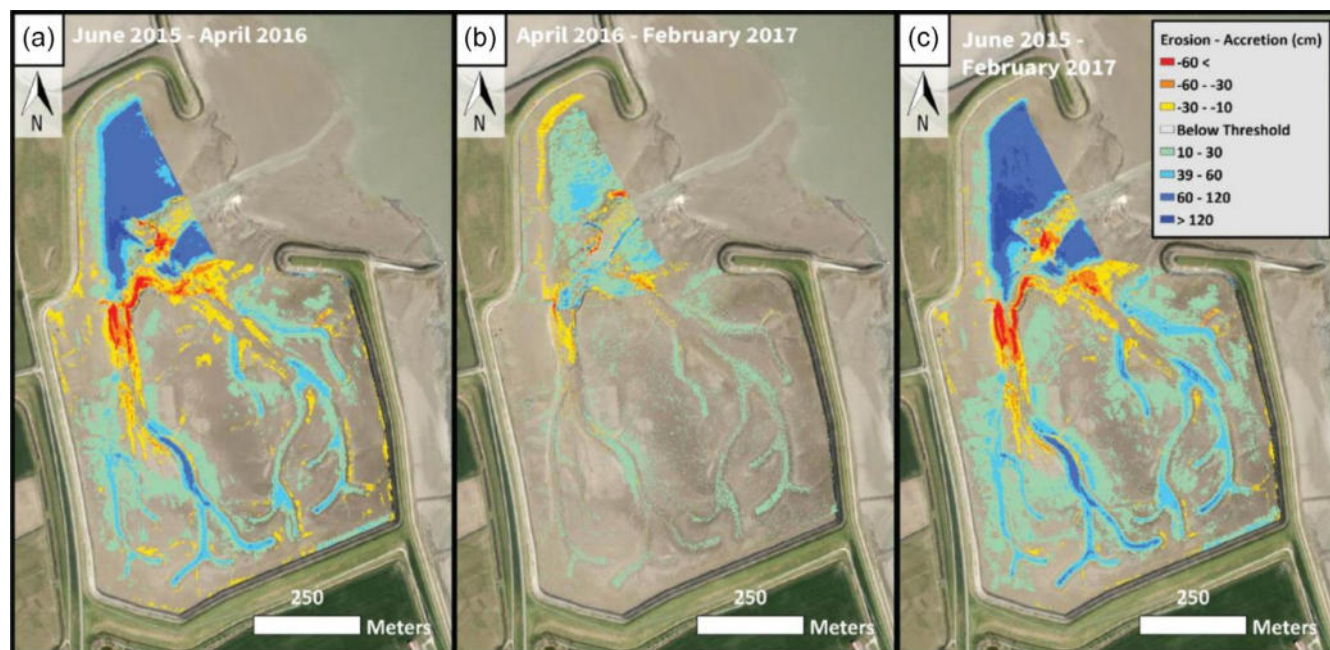


FIGURE 12 Vertical changes of the restoration project of Perkpolder regarding the intertidal flat (zone 1) and the pond area (Zone 2) from (a) June 2015 to April 2016, (b) from April 2016 to February 2017 and (c) for the whole study period from June 2015 to February 2017. The DoDs shown in this figure are made with a TCD of 0.1 m.

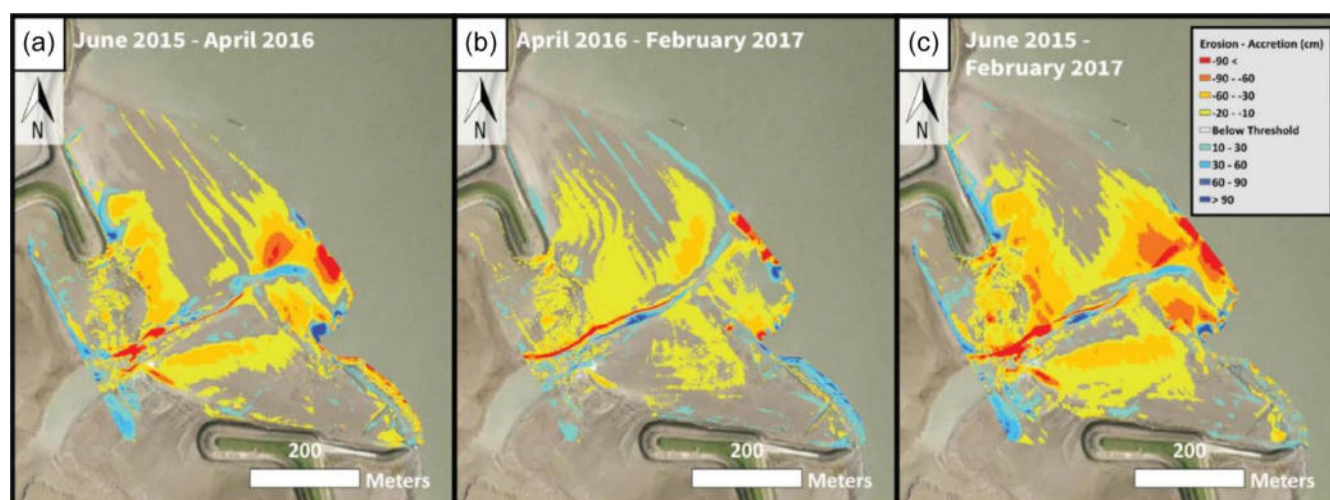


FIGURE 13 Vertical changes of the restoration project of Perkpolder regarding the inlet area (Zone 3) and the external portion (Zone 4) from (a) July 2015 to April 2016, (b) from April 2016 to February 2017 and (c) for the whole study period from July 2015 to February 2017. The DoDs shown in this figure are made with a TCD of 0.1 m.

consistent in time and accretion results because of pulses of sediment supply. However, sediment deposition on the intertidal flats of Perkpolder and Converse is highly controlled by the tide for three main reasons: (i) firstly, a higher tidal range leads to a higher water column that will submerge the intertidal flat, although it depends on the elevation of the flat with respect to the m.s.l.; (ii) secondly, the tidal currents are strong enough to transport large amount of sediment inside the system; and (iii) thirdly, the tide is also the main sediment provider because both study sites are located in locations with high sediment availability (see Table 5). The most interesting observation that stands out from the results of this study is that the combination of elevation (i.e. tidal range and inundation period), morphological complexity (i.e. presence of creeks, relict ditches and overall change of elevation),

the seasonality and, possibly, the morphological instability (i.e. erosion of its own features) are factors that controlled the depositional patterns of these intertidal flats.

The intertidal flat of the Barbarco Lagoon presented an average rate of deposition of about 36.7 g m^{-2} per tide event; this value is lower than the other study sites, which is expected from a microtidal wetland. The presence of crevasse splays, which are a typical morphological form caused by river floods, suggests that the river has a higher impact on the morphology and that the tidal currents do not alter the structure of the intertidal flat; in fact, the channels are not well developed, and they present an irregular shape caused by the floods (Brunetta, Duo, & Ciavola, 2021, 2025). Because of the absence of complex morphologies and low current velocities, the

TABLE 3 The following table presents the volume changes evaluated for the study case of Perkpolder for each morphological area (zone) with a threshold of 0.1 m.

Period		Zone 1	Zone 2	Zone 3	Zone 4
06/2015–02/2017 (whole period)	TADC (m ²)	218892	80168	27.428	122787
	TVSL (m ³)	9729 ± 3368	2678 ± 888	7860 ± 1931	39 862 ± 11 193
	TVSR (m ³)	44 640 ± 18 520	56 253 ± 7128	2268 ± 811	3421 ± 1086
	TNVD (m ³)	34 910 ± 18 824	53 574 ± 7183	–5591 ± 2095	–36 441 ± 11 246
06/2015–04/2016	TADC (m ²)	164 100	84 708	19 783	90 568
	TVSL (m ³)	10 705 ± 4374	3526 ± 1261	4186 ± 1201	25 248 ± 7910
	TVSR (m ³)	27 773 ± 12036	47 704 ± 7210	1956 ± 776	3416 ± 1147
	TNVD (m ³)	17 068 ± 12 806	44 178 ± 7319	–2230 ± 1430	–21 832 ± 7993
04/2016–02/2017	TADC (m ²)	61 204	58 136	17 377	85 480
	TVSL (m ³)	1306 ± 676	2633 ± 1148	4007 ± 1370	14 886 ± 7257
	TVSR (m ³)	7475 ± 5444	11 536 ± 4666	777 ± 367	3193 ± 1291
	TNVD (m ³)	6169 ± 5486	8904 ± 4805	–3229 ± 1418	–11 692 ± 7371

Note: TADC = Total area of detectable changes (m²); TVSL = Total volume of surface lowering (m³); TVSR = Total volume of surface raising (m³); TNVD = Total net volume difference (m³). The time intervals are from June 2015 to April 2016, April 2016 to February 2017 and June 2015 to February 2017.

elevation is the most predominant factor that influences deposition, which means that the longer the inundation period, the higher the amounts of sediment deposited (Pethick, 1981). The rates of deposition of the Po Delta site show a higher correlation when datasets from the same period (i.e. the same seasonal conditions) are chosen. Because deposition varies during different seasons, the data variability increases when using all the data from the traps of all surveys.

A completely different situation is found in the intertidal flat of Perkpolder. This restored intertidal flat is undergoing higher sediment deposition compared to the Po Delta, with average values of 64.6 g m^{−2} per tide event, and a shorter hydroperiod (i.e. between 4 and 10 h of inundation). The complex morphology and the stronger currents widely influence deposition, which depends entirely on the tide; specifically, the rates increase with distance from the inlet and decrease moving away from the channels (e.g. Crowell et al., 2025; Leonard, Hine, & Luther, 1995). Elevation with respect to the m.s.l. is less influential, meaning that for similar inundation periods, the traps collected different sediment amounts. As a consequence, this leads to high variability of the data and it explains why correlation is the lowest compared to the other dataset. In this study site, high amounts of sediment are transported by tidal currents because of the turbidity maxima, hence when tidal and river currents collide (Chen et al., 2005); however, the high rates of deposition found in this restoration project (and in the Converse one as well) could depend on a local source linked to the morphodynamic instability of the system (see Section 5.2).

An intermediate condition is found in the intertidal flat of Converse. Despite the site being characterised by exceptionally high rates of sedimentation (i.e. 154.3 g m^{−2} per tide event between 1 to 3 h of inundation), the channels do not develop through the whole intertidal flat and the effect of the elevation with respect to the m.s.l. exerts higher control on sedimentation. In this case, the distance from the inlet seems to impart less dominance on deposition; a possible hypothesis could be related to the highly deep and vertically shaped relict agricultural channels. As for the Perkpolder case, strong sedimentation could depend not only on the high concentration of

sediment in the Cumberland Basin but also on the lack of morphodynamic equilibrium (see Section 5.2), which continues to provide a sediment subsidy to the evolving tidal wetland landscape (Crowell et al., 2025).

The large variety of rates of deposition and vertical changes presented in this study not only exhibits a wide interval of sedimentation, quantifying all ranges of deposition from microtidal flats to hypertidal flats, but also highlights that all these young intertidal flats are undergoing high deposition, in most cases higher than natural old intertidal flats, with respect to their environmental and tidal context (see Section 5.1.2 for details regarding the comparison with other study cases). The main characteristics of the three intertidal flats under investigation are listed in Table 5.

5.1.2 | Comparison with deposition and vertical changes of worldwide intertidal flats

Microtidal flats and salt marshes typically accrete at ~0.2–1 cm a^{−1} (e.g. Hatton, DeLaune, & Patrick, 1983; Day et al., 1998; Scarton et al., 2000; Ciavola et al., 2002; Ibáñez et al., 2010; Jankowski, Törnqvist, & Fernandes, 2017; Yellen et al., 2021), although higher rates (~1–2 cm a^{−1}) have been reported for sites with positive dynamics, such as the Kongsmark mudflat (Andersen, Pejrup, & Nielsen, 2006) and the Po Delta (Brunetta, Duo, & Ciavola, 2021). The results show that the rates of deposition of the Po Delta range within several microtidal flats worldwide that were studied following the same or highly similar methodology (i.e. surface traps) and presented similar depositional patterns as well (e.g. Reed, 1989; Pasternak & Brush, 1998; Culbertson et al., 2004; Duvall et al., 2019; see Table 6 for detail). For example, Leonard et al., (1995) observed similar rates (winter: 13.3 g m^{−2} per tide event, summer: 23.4 g m^{−2} per tide event) in Crystal River (Florida, US), noticing that summer deposition is higher than winter. Also in this case, episodic events, such as storm deposition, which occur during winter, presented higher deposition, although lower than typical deposition during summer. Similar

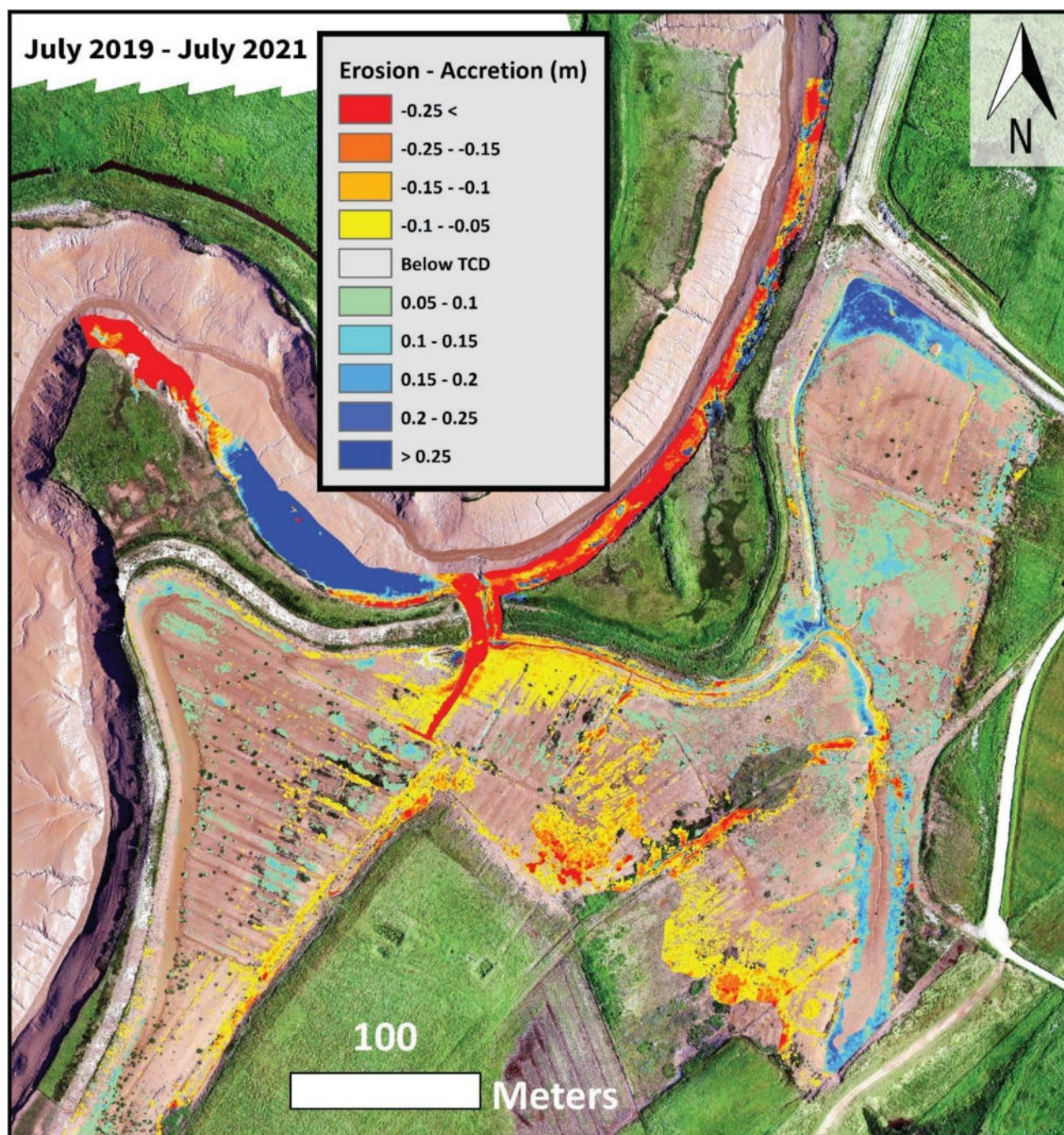


FIGURE 14 Rate of changes experienced by the restoration project of Converse between July 2019 and July 2021. In the image are included both the intertidal flat (Zone 1) of the project and the external area of the river connected with the flat by the inlet (Zones 2 and 3).

TABLE 4 The following table presents the volume changes evaluated for the study case of Converse for each morphological area (zone) with no threshold and a threshold of 0.05 m.

June 2019 to June 2021	Zone 1		Zone 2		Zone 3	
	0	0.05	0	0.05	0	0.05
TADC (m ²)	85269	28413	1356	1265	8971	8316
TVSL (m ³)	1928	1329 ± 663	660	658 ± 60	2574	2565 ± 246
TVSR (m ³)	2164	1503 ± 757	18.79	18 ± 4	1590	1582 ± 170
TNVD (m ³)	236	174 ± 1007	-641.35	-640 ± 60	-984	-982 ± 299

Note: = Total area of detectable changes (m²); TVSL = Total volume of surface lowering (m³); TVSR = Total volume of surface raising (m³); TNVD = Total net volume difference (m³). The time intervals are from June 2015 to April 2016, April 2016 to February 2017 and June 2015 to February 2017.

TABLE 5 Summary of the characteristics of the study sites.

Location	Tidal range (m)	MHT (m)	Range of elevation above m.s.l. (m)	Inundation time (h)	Total average rate of deposition (g m ⁻² per tide event)	Suspended sediment concentration (mg l ⁻¹)	Range of rate of deposition (g m ⁻² per tide event)	Sediment source	Higher rates	Average accretion rates (cm a ⁻¹)	Channels	Human intervention
Po Delta (Microtidal)	0.5	0.38	From -0.15 to 0.2	From 3:02 to 4:35	36.7	From 2.7 to 24.4 (Tesi et al., 2011)	From 1.7 to 229	River floods	Higher only in lower elevations	1.3	Channel not well developed (slow development)	Unmanaged evolution
Perkolder (Macrotidal)	4.6	2.53	From -1.27 to 1.16	From 3:56 to 9:28	64.1	From ~60 to ~100 (Van Kessel et al., 2011)	From 2.4 to 265.5	Tidal currents (turbidity maxima, Chen et al., 2005)	Next or inside the creeks (sed. increase moving far from the inlets)	6	Artificial channels under strong erosion next to the inlet but strong erosion in distant areas	Planned (dyke breaching)
Converse (Hypertidal)	13.87	6.87	From 5.14 to 6.37	From 1:27 to 2:38	154.3	From 80 to 2000 (Crowell et al., 2025)	From 1.3 to 726.5	Tidal currents (sediment plume, Amos & Tee, 1989)	Next or inside the furthest creeks (sed. increase moving far from the inlets)	Highly variable - average 0, but the most distant and depressed areas peak to 10	Artificial channels under strong erosion next to the inlet but strong erosion in distant areas	Planned (dyke breaching and removal of water control structure)

deposition and trends are found in Bradely Creek (Southern North Carolina, USA) as well, where max deposition is found next to creeks and topographic lows.

Macrotidal flats with high sediment supply are commonly characterised by higher rates of accretion compared to microtidal, with average values from 3 to 6 cm a⁻¹ (Cousins et al., 2017; Oosterlee et al., 2018; Vandenbruwaene, Meire, & Temmerman, 2012). The rates of deposition found in literature using the same methodology that regard macrotidal environments are similar to the Perkpolder case but slightly lower (e.g. French et al., 1995; Brown, 1998; Temmerman et al., 2003; Butzeck et al., 2015; see Table 6 for detail). However, each environment is highly influenced by the sediment source and the elevation of the studied area. For example, Butzeck et al. (2015) studied the Elby Estuary (northern Germany) following the same methodology presented in this paper (i.e. Petri dish trap). This macrotidal marsh (2.9–3.6 m of tidal range and MHT of 1.5 m) showed rates of deposition between ~1 and ~50 g m⁻² per tide event (bi-weekly deposition between ~20 to ~1400 g m⁻²) during 0.25 to 1.5 hours (7 to 43 h bi-weekly) of inundation at an elevation of 1.6 to 2.3 m above m.s.l.; the accretion was between 0.1 and 2 cm a⁻¹. Although this is a macrotidal environment with strong sediment input, these values are lower compared to the Perkpolder case. This can be related to the low inundation period because the rates are referred to elevations higher than the MHT, while Perkpolder is located below the MHT. On the other side, the intertidal flat of Converse, which surface is located higher than the MHT as well, has an extremely higher deposition, compared to the other intertidal flats located within the same environmental context, such as for the case of Allen Creek (van Proosdij, Davidson-Arnott, & Ollerhead, 2006), where the rates of deposition are lower, although both intertidal flats present highly similar inundation periods. Another example of similar inundation periods but lower rates of deposition with respect to the Converse study case is the Authie Estuary (France), which is a macrotidal marsh (tidal range of 4.9–8.5 m) characterised by rates of deposition from ~2.5 to ~110 g m⁻² per tide event during 0.25 to 1.8 h of inundation (Marion, Anthony, & Trentesaux, 2009). These observations show how the sediment supply highly affects how inundation period and elevation control deposition, leading to different trends that are strongly dependent on site-specific characteristics.

5.2 | Artificial morphologies affect the evolution of restoration projects

5.2.1 | Morphological instability and cannibalisation process

In most natural intertidal flats with developed creeks, the rates of deposition are low inside the channels, because tidal creeks often have strong tidal currents that prevent significant sediment accumulation (e.g. Fagherazzi et al., 2006, 2012; Li et al., 2024). However, deposition near tidal creeks is typically higher, especially on levees, because of water flow that decreases in velocity exiting the creek, leading to sediment settling (e.g. Ma et al., 2024). Consequently, the rates tend to decrease moving farther from the levees, as flow velocity decreases as well. Furthermore, deposition gradually increases moving from lower elevation to higher elevation and vice versa (e.g. Pethick, 1981; French, 1993; Marani et al., 2007).

This behaviour is highly in contrast with the results found in this study that regard the restoration projects. In the case of the restored intertidal flats (i.e. Perkpolder and Converse), there is a clear distinction between areas that are undergoing erosion and accretion. In both study cases, the inlets and their closest morphologies (i.e. the creeks inside the systems and the external portion with respect to the intertidal flat) experienced high erosional trends. It is also observed that the time for the inlet to reach stability depends on specific conditions of the inlet and the current velocities. The inlet of Perkpolder stabilised after 8 months (Brunetta, de Paiva, & Ciavola, 2019); the inlet of Converse is still undergoing erosion 2 years later as it seeks an equilibrium condition. Significant sediment build-up was observed in the distal, low-lying areas, especially at the end of the channels and, in certain cases, inside the channels. These results indicate that these systems, once connected through dyke-breach to open waters, have in common a strong morphological instability because of man-made channels (e.g. agricultural ditches) and inlets that need to find a new equilibrium with the hydrodynamic forces of the tidal currents (Crowell et al., 2025). As a consequence, these currents erode the inlets and the nearby channels, while strong accretion occurs in the most distant and low-lying areas of the intertidal flat and inside the creeks. In fact, the channels act as sediment sinks and collect higher amounts of sediment with respect to the rest of the flat.

Although the sites of Perkpolder and Converse were subjected to strong accretion because of the high suspended sediment concentration (Chmura, Coffey, & Crago, 2001; Chen et al., 2005; van Proosdij et al., 2023), it is important to consider the possibility that part of the sediment could come from the eroded inlets and the nearby areas, causing some sort of cannibalisation of the system (e.g. Crowell et al., 2025).

In the case of Perkpolder, the inlet area lost 35 000 m³ of sediment, while the overall system gained 88 500 m³ over the study period. The sediment eroded from the inlet represents 48% of the whole sediment budget, and the high sediment gain might suggest that at least part of the eroded sediment moved inside the intertidal flat and it could have provided a part of the budget. Considering the first year (i.e. 2015–2016), 61 000 m³ of net sediment were deposited inside the system, while more than 22 000 m³ eroded from the external area of the inlet; even in this case, the budget corresponds to 40%. During the last period (i.e. 2016–2017), the intertidal flat gained 15 000 m³, while the external area lost 14 000 m³, volumes that are highly comparable.

In the case of the intertidal flat at Converse, the proportions between inlet erosion and intertidal flat deposition are different. The inlet underwent strong erosion, losing 650 m³, while the intertidal flat accumulated more than 1500 m³ on the eastern side; this erosion might represent 43% of the budget. However, the external part next to the inlet presented a higher loss of sediment of about 2500 m³, overcoming the 1500 m³ that deposited in the intertidal flat, suggesting that a higher portion of sediment may come from the erosion of the meanders of the Missaguash River, rather than from the inlet alone.

Assuming that these systems are undergoing cannibalisation, the rates of deposition of Perkpolder and Converse will slowly decrease in time, flattening the exponential regression shown in Figure 15, reaching a natural behaviour (i.e. sediment does not derive from eroded human-induced morphology but from natural sources) similar

TABLE 6 Summary of characteristics and rates of deposition measured in microtidal, mesotidal and macrotidal environments studied by other authors.

Author	Location	Tidal range (m)	MHW (m)	Trap model and methodology	Rates of deposition	Inundation period/ events	Intertidal area	Characteristics and dynamics
Culberson et al., 2004	San Francisco Bay (USA)	1.2	\	7 cm petri dishes with filters; Vials for estimate errors (1 × 4.5 cm); 5 traps spaced per 25 cm parallel to channels; more than 1000 of traps; retrieve every 3 months	8.6–10.1 g m ⁻² per day – mean of the two marshes	\	High marsh	\
Leonard, Hine, & Luther, 1995	Crystal River (Florida, USA)	0.9–1.2 (Neap–Spring)	\	Filter papers on petri dishes; 8–10 traps located in 2 different locations; 1 m from the creek edge and 10 m behind the levees	Winter: 13.3 g m ⁻² per tide event Summer: 23.4 g m ⁻² per tide event	From 1 to 28 inundation events	\	- Semi-diurnal tide (irregular); Summer deposition higher than winter; - Storm deposition during winter is higher but lower than typical deposition during summer; - Sedimentation affected by proximity to creeks and season.
Leonard, 1997	Bradely Creek (Southern North Carolina, USA)	1.8 max Spring	\	Filter papers on petri dishes with 9 cm of diameter; 3 traps per site; 24 hours per trap.	13.8–63.7 g m ⁻² per day	\	Marsh	- Sedimentation higher during summer rather than during winter; - Max deposition next to creeks and topographic lows; - the results of this study indicate that site elevation exerted significant control over deposition but that its effects were largely muted by other processes; - proximity to source was one important factor.
Reed, 1989	Terrebon Bay, Louisiana (USA)	0.3–0.7 (Neap–Spring)	\	Filter papers on petri dishes with 9 cm of diameter; 3 per each site; Retrieve after 1 week	18.4 g m ⁻² per day, derived from 0.117 g per day	\	\	Higher deposition next to the main channel
Duvall et al., 2019	Chimney Pole Marsh, Virginia (USA)	1.2	0.6	Tiles left for 4 weeks; 3 next to the marsh edge, 4 in the internal part	236.34 ± 145.11 g m ⁻² per 4 weeks (8.44 g m ⁻² per day); 358.87 ± 89.67 g m ⁻² per 4 weeks (12.82 g m ⁻² per day)	\	Marsh creek and internal part, marsh edge 0.55 m, internal	High influence from waves; erosion at the edges of the creek because of waves
(Continues)								

TABLE 6 (Continued)

Author	Location	Tidal range (m)	MHW (m)	Trap model and methodology	Rates of deposition	Inundation period/ events	Intertidal area	Characteristics and dynamics
Pasternack & Brush, 1998	Bush River, Chesapeake Bay, Maryland (USA)	0.7	\	23 tiles (20 × 20 cm) left for 14 days	From -7.43 to 29.96 g cm ⁻² per year; 1.21 g cm ⁻² per year	\	marsh 0.4 m	\
Brunetta, Duo, & Ciavola, 2025	Po Delta (IT)	0.51 (1 spring)	0.38	Petri dish trap; 9 stations; 27 traps, 3 per station; 3 surveys	Winter: 20.7 g m ⁻² per tide event; Spring: 18.9 g m ⁻² per tide event; Summer: 66.8 g m ⁻² per tide event	11–13:20–6:20 h of average inundation	Intertidal flat below MHT	The sediment collected by the traps is because of tidal transport only, however most of the sediment input is related to river floods
Temmerman et al., 2003	Scheldt estuary (NL)	2.97–4.46 (Neap–Spring next to the sea), 4.49–5.93 (Neap–Spring internal part), 1.84–2.24 (Neap–Spring inner part near Ghent)	\	Plastic petri dishes with 23.3 cm diameter; Floatable cover anti-rain; 15 days, 425 traps, 17 sampling sites	Mainly from 0 to 33.33 g m ⁻² per day; 40–140 g m ⁻² per day at maximum	10–33 h	Low to higher Marsh	In general, next to the levee, similar amount but less inundation time, so faster accretion; Summer sedimentation higher due to bioturbation; Tide dominated transport
Butzeck et al., 2015	Elbe estuary (Germany)	2.9–3.6	1.5–1.8	Plastic pots of 18.9 cm and a rim of 3 cm; plastic stick of 100–120 cm 2 traps per each point spaced with 50 cm; 14 days of measurement.	20–1400 g m ⁻² bi-weekly	7–43 mean bi-weekly/0.25–1.5 h per tide	Low marsh	Higher sedimentation during fall–winter.
Brown, 1998	Hamber estuary (UK)	5.7–7.4	2.2–3.4	5.5 cm filters	few grams to 32.5 (65 g m ⁻² per day)	2, 4, 10 tidal inundations	Low to higher marsh	Higher deposition under the limit of high tide; high variation in sediment deposition.
French et al., 1995	North Norfolk (UK)	3.2–6.4 (Neap–Spring)	3.8–4 m	Filter papers (4.7 cm) on petri dishes; 350 traps	Average deposition from 2 to 40–50 g m ⁻² per tide event	\	Marsh	- Marsh height: 2–3.2 m O.D. (ordinary datum); - higher sedimentation next to creeks rather than in lower elevated areas
Brunetta, de Paiva, & Ciavola, 2019	Perkpolder (NL)	4.6	2.53	Single petri dish trap; 2 main surveys; 1 traps for a month, 2 for 2 weeks	Average 59.1–66.4 g m ⁻² per tide event (from 2.4 to 265.5 g m ⁻² per tide event)	6 h of inundation	Intertidal flat below MHT	Sediment input from turbidity maxima (Chen et al., 2005)

TABLE 6 (Continued)

Author	Location	Tidal range (m)	MHW (m)	Trap model and methodology	Rates of deposition	Inundation period/ events	Intertidal area	Characteristics and dynamics
Marion, Anthony, & Trentesaux, 2009	Authie estuary (FR)	4.89–8.54 (Neap–Spring)	\	Filter papers on petri dishes; collection every 2 weeks; 27 stations	2.47–110.6 g m ⁻² per tide event (1.8–80.7 kg m ⁻² per year) ^a	0.25–1.8 h of inundation per tide event (190–1300 h in one year)	\	- Semi-diurnal tide; - higher sedimentation in the pioneer zone (137 g m ² per day)
van Proosdij, 2006	Allen Creek, Bay of Fundy (CA)	14	5.3 m (EGM96)	3 filter per each trap; 620 traps left for a single intertidal cycle	Average deposition from 12.3 to 94.3 g m ⁻² per tide event	20 min to 2.5 h of inundation	Low to higher marsh	Sedimentation located principally below the MHWL or around; sedimentation lower during wavy events and higher during calm events; higher inundation period, higher sedimentation
The current study	Converse (NS)	11.51	6.87	Petri dish trap; 14 stations; 59 traps, 3 per station	154.3 g m ⁻² per tide (from 1.3 to 726.5 g m ⁻² per tide event)	2 h of inundation	Intertidal flat above MHT	Sediment deposition focussed on the lowest portion of the flat

^aThe values showed in 'g m² per tide' were derived from the original calculated rates. This calculation was chosen to compare the rates with the other study cases.

to other intertidal flats of their environmental context (e.g. French et al., 1995; Leonard, 1997; Marion, Anthony, & Trentesaux, 2009; Temmerman et al., 2003). In fact, compared to several similar natural coastal wetlands, the restored systems under investigation experienced higher sediment accumulation, suggesting that these restoration projects are experiencing an extra sediment input (see Section 5.1.2). However, this hypothesis works only if the sediment transported by the tide derives entirely from the inlet or both the inlet and the natural sediment source. It is important to note that it is assumed that the whole sediment eroded from the inlet has been deposited inside the intertidal flats. These datasets do not allow precise quantification of how much sediment enters or exits the system. While ebb currents generally dominate tidal network morphology (Geng et al., 2020), at Perkpolder and Converse, suspended sediment concentrations are typically higher during flood and spring tides than during ebb and neap tides (Crowell et al., 2025; Fettweis, Sas, & Monbaliu, 1998), suggesting that sediment transport is directed inside rather than outside the system.

Future studies should monitor and verify if positive trends strongly decrease in future years. However, if the cannibalisation hypothesis is true or partially true, future analyses on deposition of this type of restoration project could consider the steepness of the dataset in order to define the evolution of the intertidal flats.

5.2.2 | Morphological evolution of restoration projects

Cox et al. (2022) distinguish several strategies applied nowadays that improve the sediment injection in coastal wetlands; in the case of these studies, the main approaches can be summed up as river sediment diversion and tidal flooding.

They are based on the exploitation of the dominant sediment source using the same procedure, which consists of breaching a dyke or a levee to connect the sea or the river to the wetland. River and tidal floods both drive substantial accretion, although by different means: rivers deliver sediment in short pulses, while tides provide a steadier input. The site of the Po Delta falls within the river diversion strategy because the opening of new channels allows the river to deposit sediment within areas that were previously not subjected to deposition. Because the river is the sediment supplier, strong accretion occurs during strong floods, while slow deposition or erosion occurs during periods characterised by low flow velocities. There are several examples of case studies where river diversion was applied, such as the case of the Rhine–Meuse (NL) (van der Deijl, Perk, & Middelkoop, 2018), the Mississippi Delta (USA) (Boyer, Harris, & Turner, 1997; Day et al., 2016) and the San Francisco Bay (USA) (Miller et al., 2008). The Mississippi case is particularly similar to the Po Delta case. The river diversion technique is highly used for crevasse development and land progradation; Day et al. (2016) emphasised that episodic strong river floods and large diversions lead to a rapid coastal restoration of the system.

On the other side, the sedimentation of the intertidal flats of Perkpolder and Converse is fully controlled by the tidal currents, which cause constant deposition in time characterised by minor temporal variations, but strongly dependent on the hydroperiod, the distance from the creeks and the inlet (Crowell et al., 2025). Tidal flooding

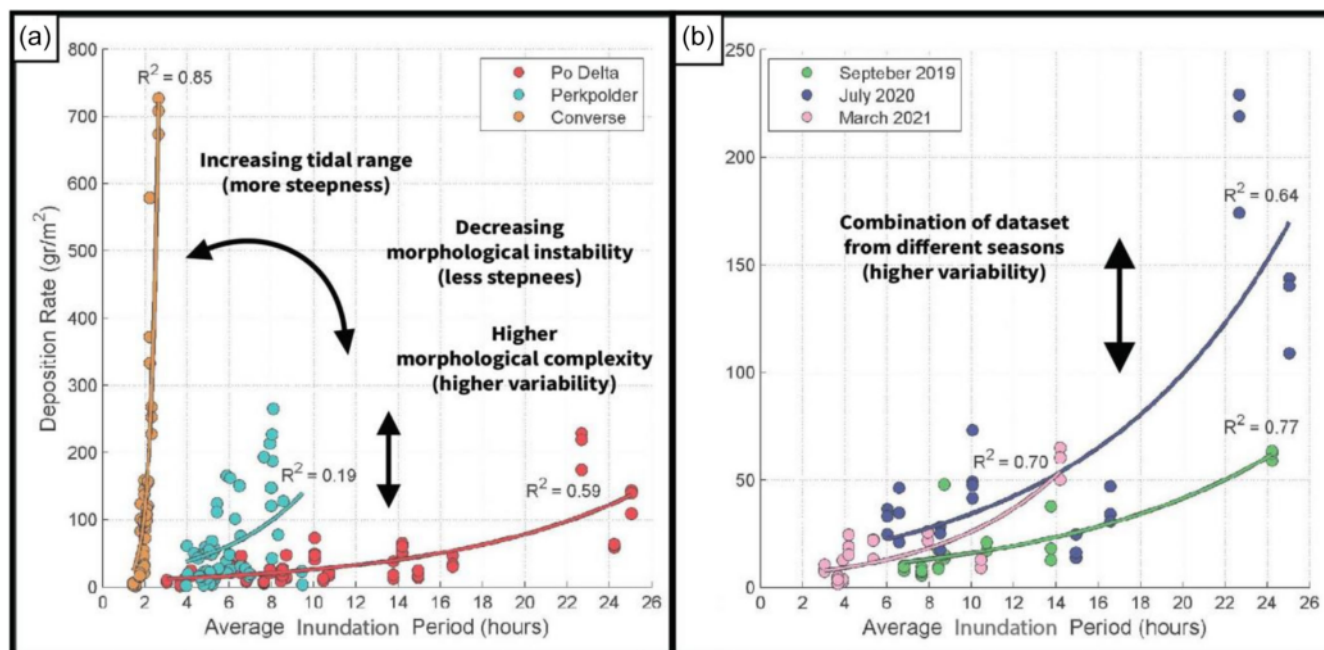


FIGURE 15 Example of future trends for deposition in restoration projects under morphological instability. (a) Tidal range and morphological instability affect the steepness of the exponential regression, while morphological complexity influences the variability of the datasets. (b) Datasets from different seasons increase variability as well.

restoration projects are under development in recent years, such as the Lippenbroek marsh (NL) (Oosterlee et al., 2018; Vandenbruwaene, Meire, & Temmerman, 2012), the Ems Estuary (DE) (Kwakernaak and Lenselink, 2015) and in Bangladesh (BGD) (Gain et al., 2017).

As described in the previous paragraph, morphological instability seems to affect the evolution of restoration projects, which follow an unnatural evolution during the first years after the opening. This behaviour is found in other restored intertidal flats, such as the Kleine Noordwaard restoration project, located in the lower Rhine–Meuse delta (The Netherlands) (Verschelling et al., 2017; van der Deijl, Perk, & Middelkoop, 2018). This microtidal wetland (tidal range of 0.2–0.4 m) is a restoration project with a similar design to the present studies (i.e. new connections between the sea and the inland areas, artificial channels) that started to be submerged by tidal currents after 2008. The average rate of vertical variations is 0.6 cm a^{-1} , which is similar to the rates of the intertidal flat of the Po Delta, and it is a typical rate for a microtidal flat with a positive trend. During the following years, an overall morphodynamic instability characterised the system, and strong accretion was found inside the creeks, while strong erosion was found inside the inlet and the channel that connects the river with the marsh system. A negative correlation between sedimentation and the elevation was found, similar to the Perkpolder dataset obtained in this study. The authors suggest a hypothesis that is in accordance with the one proposed in this study, hence that the vertical variations do not have enough control on sedimentation if compared with the morphological complexity of the system. The case study of Perkpolder, Converse and Rhein–Meuse show how artificial morphologies alter the natural deposition besides the hydrodynamic conditions and the tidal range.

Higher rates of deposition compared to natural sedimentation were detected in other restoration projects, such as in the Sacramento–San Joaquin Delta of the San Francisco Bay (California, USA), which was characterised by an average accretion of 4 cm a^{-1} ,

despite the system being a freshwater marsh (Miller et al., 2008). In certain cases, the restoration project was designed to increase deposition, such as for the case of Lippenbroek in the Netherlands (Oosterlee et al., 2018). Deposition, in this case, is controlled by a Controlled Reduced Tide (CRT), which means that the tidal range is limited to 1.3 m instead of 5.4 m; this strategy allows maintaining longer inundation periods at higher elevations in order to flatten the surface. The rates of accretion were higher than in natural marshes ($12.5\text{--}5 \text{ cm a}^{-1}$ during the first year) and decreased to 2.5 cm a^{-1} after 9 years.

5.3 | Considerations for intertidal restoration projects

5.3.1 | Intertidal flat morphology influences the ecosystem development

The morphology of a restored intertidal system influences the capacity of the ecosystem to develop and, therefore, the success of a restoration. Pioneer vegetation (e.g. *Spartina* spp.) typically colonises at elevations generally below the MHT (Bakker, 2014; De Vlas et al., 2013), defining the low marsh. Although a real elevation limit does not exist and marsh systems can develop at different intertidal ranges (Amos, 1995) because of the large number of factors that determine the vegetation growth (e.g. salinity, nutrients, drainage, etc), the influence of the landform on the ecosystem developing can be observed in the investigated study areas as well.

The intertidal flat of Perkpolder covers the Middle Flat range, and no vegetation appeared after its opening in 2015. The highest surfaces do not reach the Higher Flats and are located around 5–1.1 m above m.s.l. (based on 2017 analysis). These areas are highly restrained (i.e. 14 ha), compared to the 75 ha of the whole system,

and the most common species of *Spartina* in the estuary typically grows between 0.6 and 2 m above m.s.l. (Van der Wal, Wielemaker-Van den Dool, & Herman, 2008), suggesting that the intertidal flat may have barely reached the elevation for the pioneer plant to colonise.

On the contrary, the site of Converse (Bay of Fundy) developed stable patches of vegetation after 2 years (Crowell et al., 2025). This intertidal flat is located within the higher flats and the supratidal portion; therefore, it is more likely that the condition for a marsh to develop is found from a morphological point of view. Furthermore, the elevation of the intertidal flat of Converse ranges between the typical elevation where *Spartina* spp. grow in the context of the Bay of Fundy (Porter et al., 2015).

Overall, the observations of this study highlight how a restoration project can quickly reach its goal if the morphological conditions are favourable. Although different species require different habitat conditions and the collected dataset needs additional case studies and data, more importance should be attributed to the landform of the restored system in order to decrease the waiting time.

5.3.2 | The design of a restoration project

The design of a restoration project influences the evolution of the future morphologies and, consequently, the colonisation by vegetation.

Based on the investigations carried out in this study and worldwide studies, the most important factors that influence the morphology and, consequently, change the results of a restoration project are: (i) the connections with the sediment source, thus sediment availability, in particular if the surface of the newborn intertidal flat needs to reach higher elevations; (ii) the geographical location of the project, which is strictly linked with the sediment source; (iii) the artificial features, because morphological instability causes unusual trends of deposition that might change in time; surface elevation is part of the design as well, and it defines the future vegetation colonisation; and (iv) the hydrodynamics of the environment, which influences the sediment supply and restoration design.

5.3.3 | Young intertidal flats versus sea level rise

Based solely on the rates of vertical variations, at present, these young intertidal flats are highly able to keep pace with sea level rise. As mentioned in Brunetta et al. (2021, 2024), the intertidal flat of the Barbamarco lagoon is accreting with 1.3 cm a^{-1} , while the long time series of the Relative Sea Level Rise (RSLR) (1875–2017) is about 1.3 mm a^{-1} , and the short time series (1992–2017) show rates of 3.8 mm a^{-1} (data recorded by the Trieste tide gauge, from Da Lio & Tosi, 2019); these values are highly lower than the rates of vertical changes of the study area. The average accretion of the intertidal flat of Perkpolder (6 cm a^{-1}) is higher than the whole range of RSLR of the Scheldt Estuary ($0.3\text{--}1.5 \text{ cm a}^{-1}$ between 1931 and 2000; taken from Temmerman et al., 2004). The same condition is found in the restoration project of Converse, where the positive trend overcomes the RSLR of about 0.25 cm a^{-1} (data from the tide gauge of Saint John calculated between 1900 and 2000, taken from Greenberg et al.

(2012). However, these high rates might be inflated by the cannibalisation of internal sediment sources (e.g. inlet erosion). In the long-term, once this internal supply is exhausted, the rates might become lower and different trends are to be expected.

6 | CONCLUSIONS

This study examined the evolution of restored intertidal flats across different tidal environments, focussing on sediment deposition, vertical accretion and morphological changes. By analysing three managed realignment sites—Barbamarco Lagoon (microtidal, Italy), Perkpolder (macrotidal, Netherlands), and Converse (hypertidal, Canada)—the authors identified key factors influencing their early development. The results show that each environment is subjected to different depositional patterns that are highly dependent on the dominant process or morphological features. In the case of the Po Delta (IT), deposition follows a simple and well-known exponential relationship between elevation and inundation period (i.e. higher elevation, lower deposition). However, the rates of deposition are highly affected by seasonal variations; therefore, considering datasets from different seasons leads to lower correlation. The case of Perkpolder (NL) presented a wide range of deposition even within same elevation, indicating an important control of the morphology on sedimentation; therefore, lower correlation and high variability of the dataset occur as the morphological complexity increases. In the case of Converse (CA), although the distance from inlet and presence of ditches in the antecedent landscape affected the deposition, elevation has a stronger influence that leads to a highly correlated exponential regression.

Overall, results show that restored intertidal flats initially experience high sedimentation rates that are mostly higher than other natural wetlands, largely influenced by their main sediment supplier and morphology. This trend might be linked to the erosion of engineered features (e.g. creeks, ditches and inlets) and the high morphological instability that leads to uncommon depositional patterns compared to natural systems, such as high deposition inside the creeks or morphological depressions located far from the inlet. Erosion was high especially in the inlets and the external portion of the system, suggesting that self-cannibalisation may play a significant role in shaping these environments during the first years of development. Therefore, the design of restoration project has a high impact on the early development of a restored intertidal flat.

These findings emphasise the importance of long-term monitoring to correctly predict the evolution of managed realignment projects. Future research should focus on how the design of managed realignment projects influences sediment availability, stability and wetland sustainability over decades. Expanding the dataset to include additional restored intertidal flats worldwide will help refine predictive models for wetland evolution. Integrating hydrodynamic modelling and sediment transport simulations could improve our understanding of long-term morphological changes in these human-induced environments. This study highlights that while managed realignment is a promising tool for coastal restoration, its outcomes are highly dependent on site-specific conditions and initial design choices. Understanding these factors is critical for ensuring the long-term success and resilience of restored intertidal flats in a changing climate.

AUTHOR CONTRIBUTIONS

Riccardo Brunetta: Conceptualisation; data curation; formal analysis; investigation; visualisation; methodology and writing — original draft. **Samantha Crowell and Megan Elliott:** Data curation. **Danika van Proosdij:** Resources; supervision; writing — review and editing. **Paolo Ciavola:** Resources; supervision and writing — review and editing.

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CONFLICT OF INTEREST STATEMENT

None of the authors have a conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

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APPENDIX A

TABLE A1 This table show the sediment amount collected by traps during the surveys of September 2019, June–July 2020 and March 2021 in the Barbamarco Lagoon (Po Delta, Italy) (*w*), the elevation of each station compared to the m.s.l. (*Z*), the total inundation period (*T*), the average inundation period (*t*), and the rates of deposition per single inundation event (*S*).

Measurement period: 17–27 September 2019						
Station	Trap	<i>w</i> (g)	<i>Z</i> (m)	<i>T</i> (h)	<i>t</i> (h)	<i>S</i> (g m ⁻² /event)
P1	N	0.349	0.01	130.5	8.7	25.5
	W	0.396				
	E	1.248				
P2	N	0.288	−0.14	179.0	13.8	22.9
	W	0.407				
	E	0.852				
P3	N	0.254	0.02	126.5	8.4	12.0
	W	0.228				
	E	0.457				
P4	N	0.918	−0.23	218.0	24.2	61.5
	W	0.973				
	E	0.992				
P6	N	0.414	−0.05	150.0	10.7	19.0
	W	0.507				
P7	N	0.270	0.09	102.0	6.8	9.3
	W	0.205				
	E	0.251				
P8	N	0.266	0.04	122.0	7.6	7.2
	W	0.151				
	E	0.186				
P9	N	0.210	0.04	122.0	7.6	7.7
	W	0.216				

Note: The rates of deposition are calculated based on the tide gauge of Pila (AIPO). For more detail regarding the calculations and error evaluation, please see Brunetta, Duo and Ciavola (2025).

TABLE A2 This table show the sediment amount collected by traps during the surveys of September 2019, June–July 2020 and March 2021 in the Barbamarco Lagoon (Po Delta, Italy) (*w*), the elevation of each station compared to the m.s.l. (*Z*), the total inundation period (*T*), the average inundation period (*t*) and the rates of deposition per single inundation event (*S*).

Measurement period: 26 June to 10 July 2020						
Station	Trap	<i>w</i> (g)	<i>Z</i> (m)	<i>T</i> (h)	<i>t</i> (h)	<i>S</i> (g m ⁻² /event)
P1	N	1.436	0.01	201.0	10.1	46.1
	W	1.712				
	E	1.651				
P2	N	4.766	−0.14	272.0	22.7	207.3
	W	3.624				
	E	4.556				
P3	N	0.664	0.02	187.5	8.5	23.5
	W	1.069				
	E	0.961				
P4	N	0.386	−0.23	239.0	14.9	18.3
	W	0.453				
	E	0.687				
P5	N	2.257	−0.25	299.5	25.0	130.8
	W	2.982				
	E	2.904				
P6	N	1.226	−0.05	248.5	16.6	37.3
	W	0.886				
	E	0.797				
P7	N	1.444	0.09	157.5	6.6	34.0
	W	1.926				
	E	0.882				
P8	E	2.532				
P9	N	1.522	0.04	144.5	6.0	31.4
	W	1.376				
	E	1.025				

Note: The rates of deposition are calculated based on the tide gauge of Pila (AIPO). For more detail regarding the calculations and error evaluation, please see Brunetta, Duo and Ciavola (2025).

TABLE A3 This table show the sediment amount collected by traps during the surveys of September 2019, June–July 2020 and March 2021 in the Barbamarco Lagoon (Po Delta, Italy) (*w*), the elevation of each station compared to the m.s.l. (*Z*), the total inundation period (*T*), the average inundation period (*t*) and the rates of deposition per single inundation event (*S*).

Measurement period: 12–25 March 2021						
Station	Trap	<i>w</i> (g)	<i>Z</i> (m)	<i>T</i> (h)	<i>t</i> (h)	<i>S</i> (g m ⁻² /event)
P1	N	0.095	0.10	78.0	3.9	6.4
	W	0.440				
	E	0.132				
P2	N	0.342	−0.12	219.5	10.5	10.5
	W	0.333				
	E	0.472				
P3	N	0.789	0.06	100.5	4.2	19.6
	W	0.640				
	E	1.024				
P4	N	1.045	−0.06	182.5	7.9	24.5
	W	0.865				
	E	1.017				
P5	N	2.139	−0.20	269.5	14.2	58.4
	W	1.649				
	E	1.985				
P6	N	0.544	0.02	128.5	5.4	19.1
	W	0.929				
	E	0.910				
P7	N	0.192	0.18	39.5	3.0	8.9
	W	0.167				
	E	0.242				
P9	N	0.045	0.14	55.0	3.7	3.5
	W	0.132				
	E	0.096				

Note: The rates of deposition are calculated based on the tide gauge of Pila (AIPO). For more detail regarding the calculations and error evaluation, please see Brunetta, Duo and Ciavola (2025).

TABLE A4 This table shows the sediment amount collected by traps during the surveys of May–June 2017 in the study case of Perkpolder (NL) (*w*), the elevation of each station compared to the m.s.l. (*Z*), the total inundation period (*T*), the average inundation period (*t*) and the rates of deposition per single inundation event (*S*).

Measurement period: 15 May to 16 June 2017						
Period of inundation	Station	<i>w</i> (g)	<i>Z</i> (m)	<i>T</i> (h)	<i>t</i> (h)	<i>S</i> (g m ⁻² /event)
16/05–15/06/2017	C1–64	14.48	0.15	346.50	5.87	38.61
16/05–15/06/2017	C1–88	8.11	0.08	357.00	6.05	21.61
16/05–15/06/2017	C1–92	45.20	−0.80	479.33	7.99	120.50
16/05–15/06/2017	C1–97	9.66	0.07	357.00	6.05	25.74
16/05–15/06/2017	C1–101	55.43	−0.74	471.17	7.99	147.74
16/05–15/06/2017	C1–106	11.67	−0.15	385.83	6.54	31.12
16/05–15/06/2017	C1–112	28.57	−0.15	325.67	6.54	76.15
16/05–15/06/2017	C1–117	70.11	−0.77	476.00	8.05	186.89
16/05–15/06/2017	C1–122	38.17	−0.02	369.67	6.27	101.74
18/05–14/06/2017	C2–55	7.27	0.67	249.50	4.80	22.00
18/05–14/06/2017	C2–86	19.41	0.49	270.33	5.20	58.69
18/05–14/06/2017	C2–91	7.94	0.60	258.00	4.96	24.01
18/05–14/06/2017	C2–108	17.54	0.66	251.00	4.83	53.04
18/05–14/06/2017	C2–116	5.25	−0.32	359.83	6.92	15.86
18/05–14/06/2017	C2–118	6.56	0.56	260.83	5.02	19.83
18/05–14/06/2017	C2–126	18.51	0.41	277.50	5.34	55.99
15/05–16/06/2017	C4–64	1.42	0.48	321.33	5.18	3.53
15/05–16/06/2017	C4–109	24.52	1.11	247.50	3.99	61.22

Note: The rates of deposition are calculated based on the tide gauge of Walsoorden (Rijkswaterstaat).

TABLE A5 This table shows the sediment amount collected by traps during the surveys of May–June 2017 in the study case of Perkpolder (NL) (w), the elevation of each station compared to the m.s.l. (Z), the total inundation period (T), the average inundation period (t) and the rates of deposition per single inundation event (S).

Measurement period: 13 June to 27 June 2017						
Period of inundation	Station	w (g)	Z (m)	T (h)	t (h)	S (g m ⁻² /event)
16/06–27/06/2017	C1–82	1.66	0.47	111.00	5.29	12.40
16/06–27/06/2017	C1–83	2.78	0.19	123.50	5.88	20.81
16/06–27/06/2017	C1–84	28.51	−0.68	166.50	7.93	213.52
16/06–27/06/2017	C1–85	25.83	−0.56	160.50	7.64	193.46
16/06–27/06/2017	C1–86	22.13	0.19	123.50	5.88	165.70
16/06–27/06/2017	C1–87	21.65	0.10	127.33	6.06	162.16
16/06–27/06/2017	C1–88	30.28	−0.73	168.33	8.02	226.77
16/06–27/06/2017	C1–89	6.43	0.13	126.33	6.02	48.16
16/06–27/06/2017	C1–90	35.46	−0.76	169.83	8.09	265.53
14/06–27/06/2017	C2–71	19.81	0.41	135.83	5.43	124.60
14/06–27/06/2017	C2–72	0.81	0.56	126.83	5.07	5.09
14/06–27/06/2017	C2–73	2.98	−0.32	175.17	7.01	18.73
14/06–27/06/2017	C2–74	9.41	0.66	121.50	4.86	59.21
14/06–27/06/2017	C2–75	4.44	−0.22	169.17	6.77	27.92
14/06–27/06/2017	C2–76	7.73	0.51	128.67	5.15	48.65
14/06–27/06/2017	C2–77	3.25	0.59	126.00	5.04	20.47
14/06–27/06/2017	C2–78	10.88	0.50	129.17	5.17	68.43
14/06–27/06/2017	C2–79	20.30	−0.93	213.67	8.55	127.70
14/06–27/06/2017	C2–80	12.40	−0.83	207.83	8.31	77.99
14/06–27/06/2017	C2–81	8.05	0.66	122.17	4.89	50.63
13/06–26/06/2017	C3–62	24.93	−0.10	168.17	6.47	150.82
13/06–27/06/2017	C3–63	19.87	0.38	152.00	5.43	111.62
13/06–27/06/2017	C3–64	3.41	0.38	151.50	5.41	19.14
13/06–27/06/2017	C3–65	7.57	−0.75	224.50	8.02	42.54
13/06–27/06/2017	C3–66	5.00	0.34	154.33	5.51	28.08
13/06–27/06/2017	C3–67	0.58	−1.27	265.17	9.47	3.24
13/06–27/06/2017	C3–68	0.56	0.69	134.50	4.80	3.17
13/06–27/06/2017	C3–69	1.92	0.77	131.17	4.68	10.76
13/06–27/06/2017	C3–70	3.57	−0.30	194.67	6.95	20.02
16/06–26/06/2017	C4–52	6.66	0.61	95.50	5.03	55.15
16/06–26/06/2017	C4–53	1.60	0.62	94.17	4.96	13.22
16/06–26/06/2017	C4–54	2.65	0.58	96.33	5.07	21.89
16/06–26/06/2017	C4–55	0.28	1.16	75.00	3.95	2.35
16/06–26/06/2017	C4–56	6.15	0.94	82.17	4.32	50.92
16/06–26/06/2017	C4–57	1.82	0.78	88.67	4.67	15.06
16/06–26/06/2017	C4–58	2.86	−1.26	179.17	9.43	23.66
16/06–26/06/2017	C4–59	1.89	0.81	87.00	4.58	15.66
16/06–26/06/2017	C4–60	5.21	0.85	86.00	4.53	43.13
16/06–26/06/2017	C4–61	2.35	1.12	76.50	4.03	19.44

Note: The rates of deposition are calculated based on the tide gauge of Walsoorden (Rijkswaterstaat).

TABLE A6 The following table show the sediment amount collected by traps during the surveys of July 2021 in the study case of Converse (CA) (w), the elevation of each station compared to the m.s.l. (Z), the total inundation period (T), the average inundation period (t) and the rates of deposition per single inundation event (S).

Measurement period: 23–26 July 2021					
Station	w (g)	Z (m)	T (h)	t (h)	S(g m ⁻² /event)
N-RS1	1.552	5.874	7.82	2.02	42.29
W-RS1	1.3115				
E-RS1	0.7321				
N-RS2	6.441	5.53	9.21	2.36	249.20
W-RS2	7.5918				
E-RS2	7.1529				
N-RS3	19.0955	5.139	10.58	2.69	702.80
E-RS3	20.067				
W-RS3	20.5867				
N-RS4	2.3425	6.046	7.28	1.88	102.76
W-RS4	3.5146				
E-RS4	2.8787				
N-RS5	10.5445	5.635	8.91	2.28	428.06
W-RS5	9.4373				
E-RS5	16.4099				
N-RS6	2.4368	5.828	8.13	2.09	83.29
W-RS6	2.0497				
E-RS6	2.5944				
N-MH01	4.5071	5.868	7.93	2.05	147.33
W-MH01	4.1293				
E-MH01	3.8886				
N-MH03	0.5989	5.869	7.93	2.05	28.51
W-MH03	0.9538				
E-MH03	0.8715				
N-MH05	0.0377	6.281	6.28	1.64	3.75
W-MH05	0.1756				
E-MH05	0.1058				
N-MH09	0.0896	6.372	5.82	1.53	4.99
W-MH09	0.1836				
E-MH09	0.1511				
N-MH11	4.3987	5.749	8.55	2.19	144.65
W-MH11	3.4214				
E-MH11	4.4774				
N-MH13	2.7683	5.953	7.76	2.00	97.41
W-MH13	2.7306				
E-MH13	2.7824				
N-MH17	2.806	5.797	8.30	2.13	107.86
W-MH17	3.3084				
E-MH17	3.0552				
N-MH2A	0.4349	6.128	6.98	1.81	17.63
W-MH2A	0.5895				
E-MH2A	0.4741				

Note: The rates of deposition are calculated based on the sea level variations measured with an ADCP during the fieldwork.

TABLE A 7 This table presents the volume changes evaluated for the study case of Perkpolder for each morphological area (zone) and the threshold (TCD) used.

06/2015- 04/2016 TCD (m)	Zone 1					Zone 2					Zone 3					Zone 4				
	0	0.05	0.1	0.15	0.15	0	0.05	0.1	0.15	0.15	0	0.05	0.1	0.15	0.15	0	0.05	0.1	0.15	0.15
TADC	48 0156	28 1496	16 4100	10 4024	10 4024	10 8604	96 192	84 708	75 456	75 456	42 502	29 261	19 783	14 245	20 0479	13 1071	90 568	25 248	22 905	68 454
TVSL	15 994	13 869	10 705	8538	4071	3908	3526	3075	3075	3075	4630	4484	4186	3788	28 693	27 577	± 5444	± 7910	± 9133	± 9133
TVSR	35 669	33 110	27 773	22 580	± 11705	48 445	48 240	47 704	46 964	± 9955	2633	2394	1956	1647	5091	4224	± 1110	± 1147	± 1135	± 1135
TNVD	19 675	19 240	17 068	14 042	± 12337	44 373	44 332	44 178	43 889	± 10 048	-1996	-2090	-2230	-2141	-23602	-23 353	± 5556	± 7993	± 9204	± 9204

Note: TADC = Total area of detectable changes (m²); TVSL = Total volume of surface lowering (m³); TVSR = Total volume of surface raising (m³); TNVD = Total net volume difference (m³). The time intervals are from June 2015 to April 2016, April 2016 to February 2017 and June 2015 to February 2017.

TABLE A 8 This table presents the volume changes evaluated for the study case of Perkpolder for each morphological area (zone) and the threshold (TCD) used.

04/2016- 02/2017 TCD (m)	Zone 1					Zone 2					Zone 3					Zone 4				
	0	0.05	0.1	0.15	0.15	0	0.05	0.1	0.15	0.15	0	0.05	0.1	0.15	0.15	0	0.05	0.1	0.15	0.15
TADC	47 9460	243 724	61 204	14 364	14 364	10 6852	78 380	58 136	43 752	43 752	42 088	26 775	17 377	11 621	20 1937	13 8526	85 480	44 197	44 197	44 197
TVSL	2776	1925 ± 774	1306 ± 676	918	± 544	3699	3289	2633	2086	± 1077	4743	4487 ± 991	4007	3461	19354	18193	± 5693	± 7257	± 7257	± 7257
TVSR	25172	19 853 ± 11411	7475 ± 5444	2306	± 1611	12869	12 458	11 536	10 232	± 5486	1209	1027 ± 347	777	584 ± 323	4791	4096	± 1234	± 1291	± 1291	± 1291
TNVD	22395	17 928 ± 11438	6169 ± 5486	1388	± 1700	9169	9169	8904	8146	± 5591	-3534	-3459	-3229	-2876	-14562	-14096	± 5825	± 7371	± 7371	± 7371

Note: TADC = Total area of detectable changes (m²); TVSL = Total volume of surface lowering (m³); TVSR = Total volume of surface raising (m³); TNVD = Total net volume difference (m³). The time intervals are from June 2015 to April 2016, April 2016 to February 2017 and June 2015 to February 2017.

T A B L E A 9 This table presents the volume changes evaluated for the study case of Perkpolder for each morphological area (zone) and the threshold (TCD) used.

06/2015- 02/2017	Zone 1					Zone 2					Zone 3					Zone 4				
	TCD (m)																			
	0	0.05	0.1	0.15		0	0.05	0.1	0.15		0	0.05	0.1	0.15		0	0.05	0.1	0.15	
TADC (m ²)	468708	33 5408	21 8892	14 088		10 9008	9206	80 168	72 568		48 295	35 876	27 428	21 471		20 6229	156 875	122 787	98 910	
TVSL (m ³)	12674	11 430 ± 2790	9729 ± 3368	8236 ± 3290		3180	2980 ± 641	2678 ± 888	2399 ± 1006		8413	8225 ± 1.198	7860 ± 1931	7383 ± 2344		42812	41 915 ± 6892	39 862 ± 11 193	37 178 ± 13669	
TVSR (m ³)	54720	52 050 ± 13979	44 640 ± 18520	36 191 ± 17 841		57156	56 874 ± 3961	56 253 ± 7128	55 557 ± 9879		2745	2562 ± 595	2268 ± 811	1979 ± 876		4563	4047 ± 952	3421 ± 1086	3031 ± 1167	
TNVD (m ³)	42046	40 619 ± 14 255	34 910 ± 18 824	27 955 ± 18 142		53975	53 894 ± 4013	53 574 ± 7183	53 158 ± 9930		-5668	-5663 ± 1338	-5591 ± 2095	-5403 ± 2502		-38249	-37 868 ± 6957	-36 441 ± 11 246	-34 148 ± 13 719	

Note: TADC = Total area of detectable changes (m²); TVSL = Total volume of surface lowering (m³); TVSR = Total volume of surface raising (m³); TNVD = Total net volume difference (m³). The time intervals are from June 2015 to April 2016, April 2016 to February 2017 and June 2015 to February 2017.