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The Morphological Development of Restored Mainland Salt Marshes Along the East Frisian Wadden Sea Coast

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Abstract

Foreland salt marshes along the East Frisian coast serve as nature-based solutions bridging nature conservation, coastal flood and erosion risk management, and climate-change adaptation. To restore foreland salt marshes anthropogenically altered due to land reclamation, topsoil removal is used as an ecological restoration measure. Parallelly, the excavated clay material can be utilized for coastal flood and erosion risk management projects. This study evaluates the morphological development of the topsoil removal sites Leybucht and Manslagt by monitoring sedimentation dynamics using sedimentation–erosion bars and tracking relief evolution with digital terrain models (DTMs), with tidal creek development specifically quantified using Strahler stream order analysis. Results demonstrate that topsoil removal successfully initiates processes, developing meandering tidal creeks and relief characteristic of natural salt marshes and improving the morphological habitat quality as a substantial basis for improvement of biological habitat quality. Ultimately, topsoil removal proves to be an effective restoration strategy, highlighting how conservation-driven measures can create a win-win situation with coastal flood and erosion risk management needs.

Keywords: renaturation; clay pit; salt marsh management; nature conservation; coastal flood and erosion risk management (CFERM); nature-based solutions (NBS)

1. Introduction

Globally, coastal systems are increasingly challenged by human activities and climate-induced pressures, such as sea-level rise, and changes in temperature and hydromorphological dynamics [1–4]. Concurrently, they must address the growing demands of Coastal Flood and Erosion Risk Management (CFERM) [5–8]. Therefore, coastal systems have to be highly resilient and adaptable to these changing conditions. For regional coastal management, this necessitates the optimization of ecosystem condition [9–11]. As a result, nature-based solutions (NBSs) are attracting growing interest in research and practice [10,12–14]. This trend is also reflected in large-scale projects and initiatives, such as MANABAS Coast, CoastAdapt, or the German Federal Action program for natural climate protection (ANK) [15–17].

The Wadden Sea represents a unique ecosystem, and it was designated a UNESCO World Heritage Site in 2009 in recognition of its outstanding natural value [18]. This

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dynamic landscape is protected through its inclusion in the European Natura 2000 network [19].

Within this context, salt marshes constitute a significant element of the coastal system, uniquely combining ecological and CFERM functions [20,21]: First, they provide an important habitat for rare and endangered flora and fauna in the Wadden Sea area, thereby contributing to biodiversity preservation [22,23]. Therefore, they are classified as coastal and halophytic habitats (types 1310 and 1330) under the EU Habitats Directive (European Council 1992) and represent important biotopes protected by national nature conservation legislation in Germany [24,25]. Second, they play a major role as legally defined, nature-based coastal protection elements in CFERM systems (CPSL), owing to their capacity for wave attenuation, flood risk reduction, and dike foot protection [13,26–28]. In the context of climate-change adaptation and rising sea levels, their preservation and sustainable development are of utmost importance for long-term CFERM [21,29–31]. Beyond these ecological and physical functions, their capacity as a carbon sink is gaining increasing importance in the face of climate change [32,33].

Along the mainland coast of the southern North Sea, particularly in Germany and the Netherlands, many salt marshes were created as part of historical land-reclamation efforts [34–36]. To promote sedimentation and vegetation development, thereby enabling livestock grazing, a network of ditches and drainage channels was established within the pioneer zones, in combination with sedimentation fields, as well as in the salt marshes to ensure drainage [34,37–39]. In the past, salt marshes were also a resource for gaining suitable material for dike construction through the excavation of deep clay pits [40]. However, with the increasing importance of nature conservation, this practice was severely restricted, as it was considered a significant anthropogenic interference to the habitat [41]. However, the results of a ten-year monitoring project assessing the ecological development of a clay extraction site at the Petersgroden foreland salt marsh (Jade Bay) indicated that topsoil removal in anthropogenically influenced salt marshes can significantly improve habitat quality while accounting for conservation considerations. Based on these findings, specific recommendations were derived for clay pit design, considering nature conservation and legal environmental requirements [41]. From the late 1990s onward, topsoil extraction re-emerged as a focal point in coastal management for foreland saltmarshes. Due to artificial ditch structures and the dominance of couch grass (*Elymus athericus)* vegetation cover, these systems are classified as anthropogenically modified, resulting in an unfavorable ecological conservation status [42–44]. Integrated management goals were defined and plans were established, aiming to improve the ecological status while simultaneously safeguarding the CFERM function of the salt marshes [21,39]. Lowering the ground level by removing topsoil was identified as a potential measure to enhance their conservation value [21,45,46]. This approach aims to remove anthropogenic structures while simultaneously initiating the natural, dynamic development of pioneer zones and lower salt marshes, thereby promoting the formation of natural drainage networks characterized by tidal creeks (Annex 1.7, [43,47]). Based on salt marsh management plans and in close coordination with the Lower Saxony Wadden Sea National Park Authority (NLPV), the Lower Saxony Coastal Protection and Nature Conservation Agency (NLWKN) optimized the design of soil extraction sites to serve both nature conservation and CFERM objectives [39,45]. These restoration measures were implemented in foreland salt marshes along the northwestern mainland coast of the German federal state Lower Saxony. Located within the Leybucht and Manslagt regions, they cover a total extent of approximately 9 and 11 ha (Figure 1). The topsoil removal conducted in 2019/2020 in the Leybucht and 2020 in Manslagt aimed to enhance this conservation status by promoting the natural succession of pioneer zones, lower salt marshes, and naturally developing tidal creek networks, while utilizing the excavated clay for CFERM through local dike

strengthening. Following completion, the subsequent geomorphological evolution of the site has been systematically monitored. The results provide morphological insights into topsoil removal as a combined ecological restoration and CFERM measure. The objective of this paper is to document the implementation of this measure across the study sites and to analyze and evaluate the morphological processes. Finally, this study assesses whether the intervention successfully enhanced the area's nature conservation value by comparing the morphologically assessed conservation status before and after the measure. This study provides empirical field data for large-scale initiatives such as MANABAS Coast, demonstrating how topsoil removal can operationalize NBS to align ecological enhancement with regional coastal flood and erosion risk management CFERM strategies.

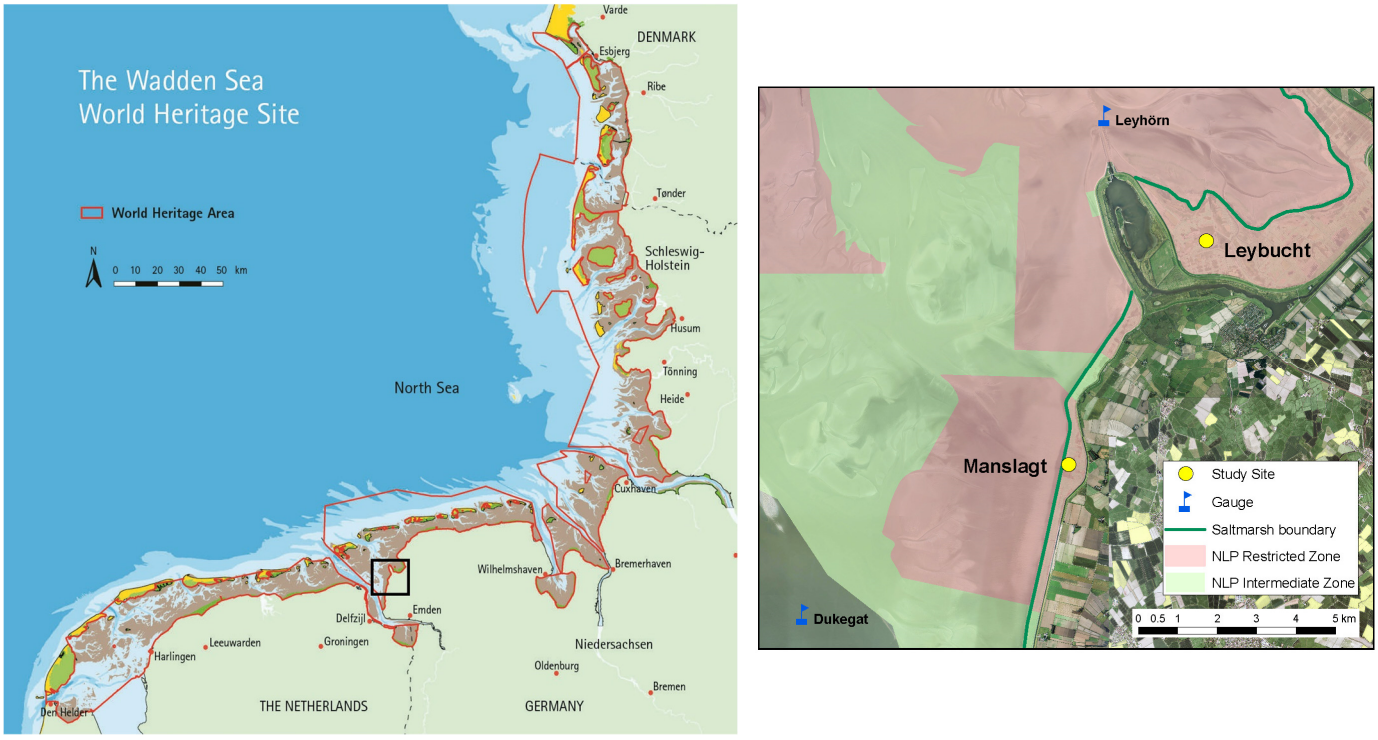


Figure 1. Southern North Sea with the Wadden Sea World Heritage Site [48] (**left**) and the Manslagt and Leybucht study sites (**right**, aerial pictures source: LGLN 2024 [49]; NLWKN 2024 [50]).

2. Project Description and Methods

2.1. Initial State of the Study Sites

The study sites, referred to as 'Leybucht' and 'Manslagt' (Dyksterkruger Heller), are located northwest on the North Sea mainland coast of Lower Saxony in Germany. Both sites are situated in the restricted zone of the Lower Saxony Wadden Sea National Park which is designated as part of the NATURA 2000 Network (Figure 1) (Appendix 2, [24]).

Leybucht: To extend the foreland salt marshes in the Leybucht and enable their agricultural use for cattle grazing, artificial drainage structures were built until the 1980s. Consequently, large parts of the area are characterized by anthropogenic drainage structures, a lack of dynamic processes, and missing connection to the tidal system. However, the sheltered location within the bay allows for the development of natural salt marshes [45]. The assessment of the ecological status according to the NLWKN [45,51] states anthropogenically influenced areas with a medium to poor (C) rating due to dominance of Couch grass (*Elymus athericus*). The seaward areas with naturally developing salt marshes are rated as good to very good (B, A).

Manslagt: The foreland salt marsh 'Dyksterkruger Heller' is a location exposed to wave action at the outer Ems estuary and was artificially created by nourishment of

different sediment types and secured against erosion by a foreshore revetment between 1968 and 1970 to protect the primary dike at this location [45]. The initial state of the area was shaped by anthropogenic activities, characterized by narrow drainage structures (Figure 2). The vegetation is primarily composed of upper salt marsh, with notable dominant couch grass (*Elymus athericus*) stands, and small areas with pioneer and lower salt marsh stages. There is no natural transition from the salt marsh to the adjacent mudflats. The ecological conservation status was assessed as medium to poor (C), with the exception of some water pools/salt pans, which were evaluated with a good (B) status [45,51].



Figure 2. Typical drainage network in the Manslagt foreland salt marsh, characterized by ditches and field drains, with ditches spaced 10 m apart (24 July 2024).

Hydrologically, the areas are characterized by a semidiurnal tidal regime. Hydrographic gauges in the immediate vicinity of the study areas include the Leyhörn and Dukegat gauges (Figure 1; Table 1).

Table 1. Main hydrological parameters for the 2021–2025 observation period at the Leyhörn and Dukegat gauges (mean high water = MHW; elevations are relative to NHN (German vertical datum)) [52,53].

Gauge	MHW [m NHN]	MHW [m NHN]	MHW [m NHN]
Leyhörn	1.41	−1.21	2.62
Dukegat	1.31	−1.37	2.68

Inundation frequencies for the elevation levels mean high water (MHW) +30 cm, MHW +70 cm (corresponding approximately to the mean initial ground level of the salt marshes), and MHW +1 m at the Leyhörn tidal gauge are exemplarily shown in Table 2 for the 2022 to 2023 and 2023 to 2024 sedimentation–erosion-bar measurement intervals.

Table 2. Number of water level threshold exceedances during two monitoring periods at the Leyhörn gauge (mean high water = MHW, elevations are relative to NHN (German vertical datum)) [52].

	10 October 2022 to 15 August 2023	15 August 2023 to 4 October 2022
MHW + 30 cm	98	170
MHW + 60 cm	21	42
MHW + 100 cm	1	13

2.2. Planning and Execution of the Projects

In the planning phase, the selection of the areas and the planning of the measure were based on nature conservation and CFERM criteria. The dike foreland of the Leybucht and Manslagt were identified in the salt marsh management plan [45] as potential areas for restoration measures due to the poor ecological status of the salt marsh habitats. The aim of the measures is to improve the conservation status of the habitat type 'Atlantic salt marsh' (1330) [43,45] by enabling natural dynamics and creating suitable sites for the development of natural salt marsh succession. The management plan considers lowering the ground level at certain areas to be a suitable measure. The extracted soil material can be used to reinforce dikes, resulting in a win-win situation for nature conservation and to improve flood risk management by dike strengthening.

In both cases, the measures were implemented according to a similar general scheme. The upper soil was removed, including the upper root-permeated top-soil with excavators up to the target height based on the vegetation zonation of salt marshes. The clay was transported with dumpers via temporary steel plate roads. The lateral edges were naturally shaped with mild slopes, featuring a gradient of 1:10 to 1:50. To ensure that the forelands function as intended for CFERM, the measures were kept 200 m away from the dike.

Leybucht: In 2019/2020, parts of the anthropogenically influenced salt marshes in the Leybucht, the 'Hauener Hooge', were restored. At an area comprising approx. 9 ha, extensive soil removal was carried out to create sites for pioneer and early succession stages of the salt marsh, to remove anthropogenic structures and initiate natural creek initiation, to connect sinks to the tidal regime and to partially dismantle a summer dike. The ground level was lowered from approx. +1.8 to 2.3 m NHN down to +1.2 to +1.5 m NHN in two steps. First, in 2019, the southern part of the study site was executed, followed by the northern part in 2020.

Manslagt: In 2020, a renaturation measure to compensate for the seaward extension of a dike was carried out. On approx. 9 ha in the anthropogenically influenced foreland salt marsh, the ground level was adjusted, and ditches were filled in to enable the development of natural tidal creeks structures and to rejuvenate the habitat. The ground level was lowered from the initial height of +1.8 to 2.4 m NHN to +1.30 to +1.60 m NHN. At the Manslagt site, the terrain featured a planar topography with execution-related variations ranging from +1.2 to +1.4 m NHN. A tidal creek for the drainage of the dike foot was shaped, featuring a target height of +1.0 to +1.1 m NHN.

A comparison of the key environmental and structural parameters of both study sites is provides in Table 3, and an overview of the sites shown in Figure 3.

Table 3. Key environmental and structural parameters of the study sites, Leybucht and Manslagt, before and after restoration.

Parameter/ Characteristic	Leybucht	Manslagt
Geographic location and exposition	Sheltered bay location on the North German mainland coast	Exposed location at the outer mouth Ems estuary on the North German mainland coast
Study area (ha)	Approx. 9 ha total area, reduced to 7.6 ha for analysis (to avoid edge effects)	Approx. 9 ha total area, reduced to 6.7 ha for analysis (to avoid edge effects)
Hydrological parameters	Mesotidal regime; see Table 1	Mesotidal regime; see Table 1
	Initial state	

Habitat assessment/ vegetation	Moderate to inadequate (C) to dominance of Couch grass (*Elymus athericus*); areas located seaward are rated good to very good (B, A)	Moderate to inadequate (C) to dominance of Couch grass (*Elymus athericus*), exception of shallow water zones/pools (B)
Initial height	+1.8 to +2.3 m NHN	+1.8 to +2.4 m NHN
	Measure	
Implementation schedule	Carried out in two phases: Southern section in 2019; northern section in 2020	Fully implemented in 2020
Target heights	+1.2 to +1.5 m NHN; north–south gradient	+1.3 to +1.6 m NHN; flat topography, main channel +1.0 to +1.1 m NHN
Monitoring duration	October 2022 to October 2025	September 2021 to September 2025



Figure 3. Both study sites are in a mesotidal area, with mean tidal range. Location of the study area Leybucht (**left**) and Manslagt (**right**) (Red borders indicate the boundaries of the study areas) (aerial pictures source: NLWKN 2024 [50]).

2.3. Methods

2.3.1. Monitoring Data

Following project finalization, systematic monitoring was carried out to analyze the temporal development and spatial distribution of surface elevation changes, as well as the evolution of morphological features such as tidal creeks. To achieve this, a dual-method approach was employed: sedimentation–erosion bars (SEBs) were installed at both study sites, and digital terrain models (DTMs) derived from Unmanned Aerial Vehicle (UAV) (DJI Technology Co., Ltd., Shenzhen, China) surveys were generated. SEBs represent an effective method for recording sediment accretion and erosion rates over periods of several months to years [54,55]. However, to scale these observations to a landscape level, DTMs were derived from aerial surveys. While SEBs capture localized sediment dynamics, DTMs complement this approach by providing comprehensive insights into macro-scale morphological developments across the entire study area [55]. Monitoring intervals

varied across campaigns, which will be taken into account when evaluating annualized rates.

(a) Sedimentation–erosion bars

The SEBs were constructed using two steel poles with a diameter of 7 cm and a length of 1.5 m, which were anchored into the ground using an earth auger tip end until a stable position was achieved. At a depth of approximately 0.5 cm below surface, a stable layer prevents the SEB from vertical movements due to subsidence and soil shrinkage. The poles are aligned horizontally and positioned at a distance of two meters apart. The elevation of the SEBs relative to the German reference datum NHN was determined using GNSS measurements. During monitoring, an aluminum bar with a rectangular profile featuring 17 holes at 10 cm intervals was placed on top of the poles to measure the distance to the soil surface using a sounding rod (Figure 4). Annual changes in bed level [mm] were calculated from the difference between consecutive measurements at each specific location and subsequently annualized [mm/a].

Five SEBs were installed across the Leybucht study area in October 2022, with subsequent measurements taken until October 2025 (Figure 5). In Manslagt, four SEBs and one reference SEB were deployed in September 2021, followed by four monitoring campaigns through September 2025 (Figure 5). Exact dates for all measurement campaigns are provided in Table 4.

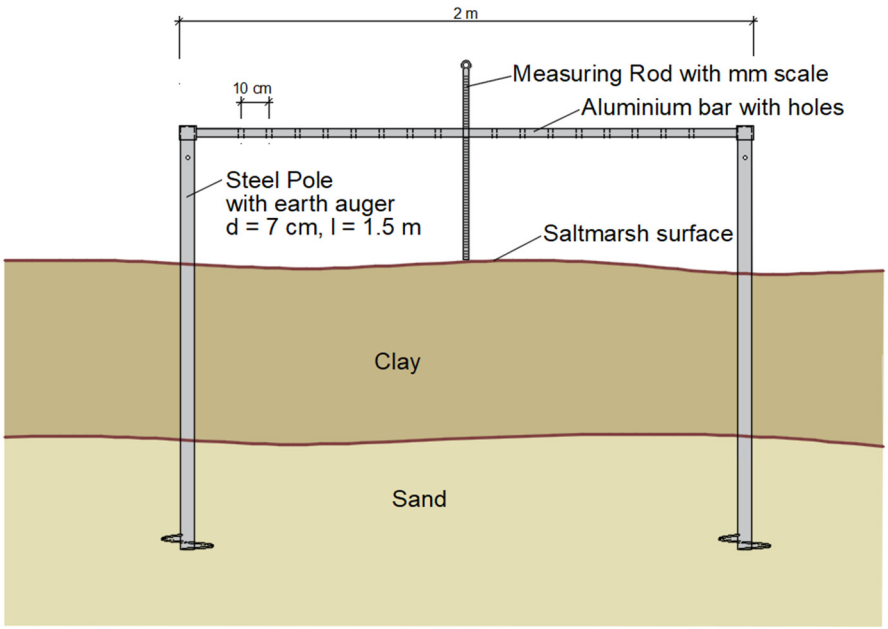


Figure 4. Sedimentation–erosion bar (SEB).

Table 4. Overview of UAV (Unmanned Aerial Vehicle)-based monitoring campaigns performed.

Year	Manslagt			Leybucht		
	SEB Date	**DTM Date**	**DTM Format, Type**	**SEB Date**	**DTM Date**	**DTM Format, Type**
2020	-	26 November 2020	0.1 m, UAV photogrammetry	-	25 November 2020	0.1 m, UAV photogrammetry
2021	24 September 2021	1 September 2021	0.1 m, UAV photogrammetry	-	17 April 2021	1 m, Airborne LIDAR

2022	10 October 2022	30 September 2022	0.1 m, UAV LIDAR	10 October 2022	21 September 2022	0.1 m, UAV LIDAR
2023	11 August 2023	15 September 2023	0.1 m, UAV LIDAR	15 August 2023	18 August 2023	0.1 m, UAV LIDAR
2024	4 October 2024	5 September 2024	0.1 m, UAV LIDAR	4 October 2024	12 August 2024	0.1 m, UAV LIDAR
2025	10 September 2025	12.12.2025	0.1 m, UAV LIDAR	1 October 2025	-	0.1 m, UAV LIDAR

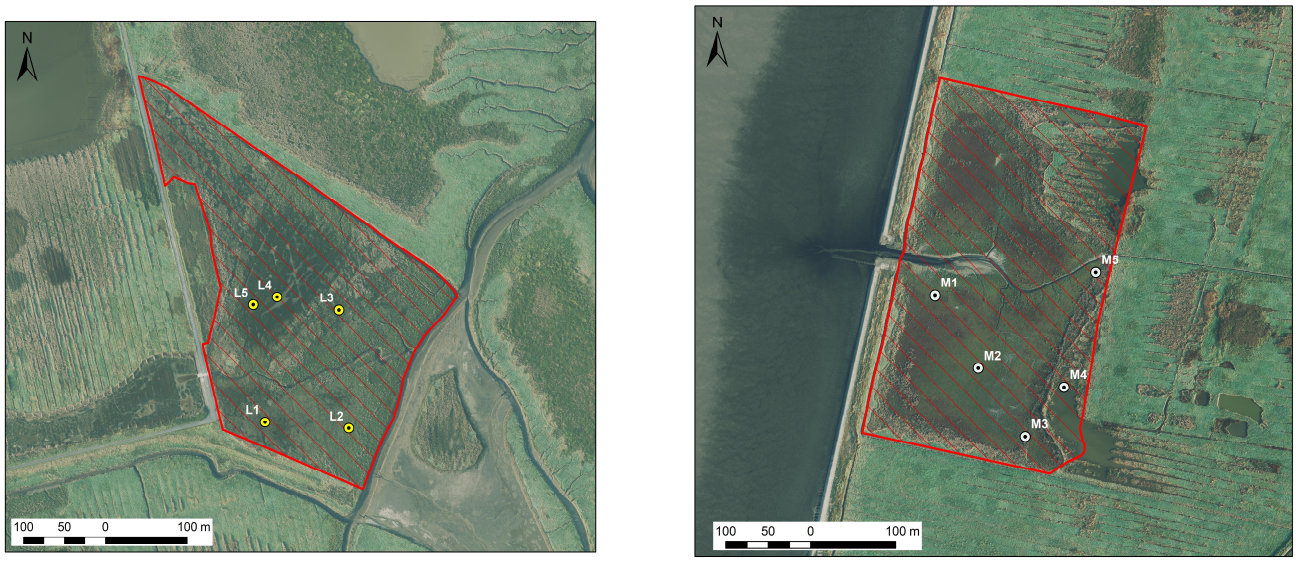


Figure 5. Spatial distribution and locations of installed SEBs in the study sites, Leybucht (**left**) and Manslagt (**right**) (Red borders indicate the boundaries of the study areas), Numbering of the sedimentation–erosion bars in Leybucht L1–L5, and in Manslagt M1–M5 (aerial pictures source: NLWKN 2024 [50]).

(b) Digital terrain models

To monitor morphological changes at the two study sites, a total of 13 airborne remote-sensing surveys were conducted between November 2020 and December 2025, utilizing airborne photogrammetry and airborne/UAV laser scanning (Table 4). Surveys were strictly scheduled during low-tide windows to capture the exposed intertidal surface and minimize data gaps or errors caused by water coverage. All datasets were georeferenced in the ETRS89/UTM Zone 32N (EPSG:25832/6-digit) coordinate reference system, using DE_DHHN2016_NH as the vertical datum. Across both study sites and regardless of the applied remote sensing method, a consistent horizontal accuracy of < 5 cm was achieved throughout the entire observation period.

Vertical accuracy exhibited a clear dependency on the surveying method and surface conditions. Photogrammetric surveys conducted in November 2020 and September 2021, as well as the initial Airborne Laser Scanning (ALS) campaigns in April 2022 (Leybucht) and September 2022 (Manslagt), achieved a vertical accuracy of <5 cm. In contrast, eight subsequent ALS surveys conducted between September 2022 and December 2025 showed a reduced vertical accuracy of <10 cm, which is primarily attributed to partial effects of vegetation cover impairing the LiDAR ground-point classification.

To mitigate vegetation-induced effects on vertical accuracy, high-resolution digital terrain models (DTMs) with a spatial resolution of 10 cm were generated from the LiDAR point clouds. Vegetation points were removed using the automated ground classification (Autoclean filter) implemented in Trimble Business Centre 2025.20 [56]. Additionally,

residual artifacts caused by dense vegetation were manually corrected based on high-resolution orthophotos to delineate unvegetated ground. Furthermore, an additional DTM with a spatial resolution of 1 m was acquired for the Leybucht site in April 2021, and it is exclusively used in the subsequent analysis to delineate tidal creek networks.

Using Esri ArcMap 10.8.2 [57], surface-elevation changes were quantified by generating digital elevation models of difference across the entire study area for the entire observation period. Although digital filtering was applied to extract bare-earth terrain elevation, a residual risk of slightly overestimating surface elevation in densely vegetated areas remains. Baseline surveys at the Leybucht and Manslagt study sites were conducted immediately following the completion of the restoration measures, with ongoing monitoring carried out in the subsequent years (Table 4). To minimize boundary effects, a 5 m buffer was clipped along the perimeter of each site, resulting in net analyzed areas of 7.6 ha for Leybucht and 6.7 ha for Manslagt.

2.3.2. Detection of Tidal Creek Networks

The morphological development of the tidal creek networks was quantified using three primary metrics: total creek length [m], density [m/ha], and annual growth rate [%]. The growth rate was determined by, first, calculating the difference of the total creek length for both the consecutive annual and the entire measuring; and, second, calculating the relative change in percentage. To extract the creek networks from the DTMs, 'flow accumulation' (based on threshold of 10.000 cells) and 'slope' algorithms (utilizing a threshold of 3 degrees) were executed within ESRI ArcMap 10.8.2 [57]. However, flow accumulation methods are prone to artifacts and errors in low-gradient, shallow intertidal zones, as previously documented by Liu et al. [58]. To mitigate these limitations and optimize network detection, georeferenced aerial photographs were additionally integrated into the workflow for visual detection and manual validation, leveraging their proven efficiency in identifying micro-topographic drainage features such as creeks [59].

For structural classification, the quantitative method of the Strahler stream order method [60] was applied. Within this framework, creek segments are numbered consecutively, initiating with first-order (order 1) designations at the terminal fingertip tributaries. The confluence of two segments of the same class increases the downstream segment's hierarchical order by one.

Morphological parameters were statistically evaluated across both the analyzed entire drainage network and within individual creek orders. To prevent methodological inconsistencies, the anthropogenically modified main tidal creek at the Manslagt site and the main creek in the Leybucht were excluded from the evaluation of natural morphological indicators.

To quantitatively assess network complexity and structural hierarchy, the ratio of the number of segments at adjacent ordinal levels was calculated as the bifurcation ratio [60]. The bifurcation ratio is calculated using the following formula:

$$Bifurcation\ Ratio\ (Rb) = \frac{N_u}{N_{u+1}}$$

where N_u represents the number of segments at the respective order level. This enables a structural comparison of the developing creek network with near-natural reference systems.

2.3.3. Nature Conservation Status of the Habitats

The morphological conservation status of the 'Atlantic salt marshes' (Habitat Type 1330) was assessed following the methodology framework for Lower Saxony [61] (Table 5). This incorporates the abiotic criteria 'tidal creeks' and 'relief', utilizing the available

monitoring datasets. To quantify morphological changes over time, a baseline assessment from the period of 2015–2017 [51] is available, which is utilized for comparison with the actual state.

Table 5. Morphological conservation status assessment and classification methodology (Annex 1 [61]).

	A Favorable	B Unfavorable–Inadequate	C Unfavorable–Bad
Completeness of habitat-specific structures:	Present	Extensively present	Partly present
Relief	Natural relief, e.g., with raised tidal creeks, vegetation-poor pans, […]	Natural relief less pronounced	Uniform topography due to anthropogenic structures consisting of ditches and beds
Tidal creeks	Natural system of meandering creeks	Present, but altered by artificial drainage, or development of natural creek systems following abandoned artificial drainage	Little-to-no meandering tidal creeks present

3. Results

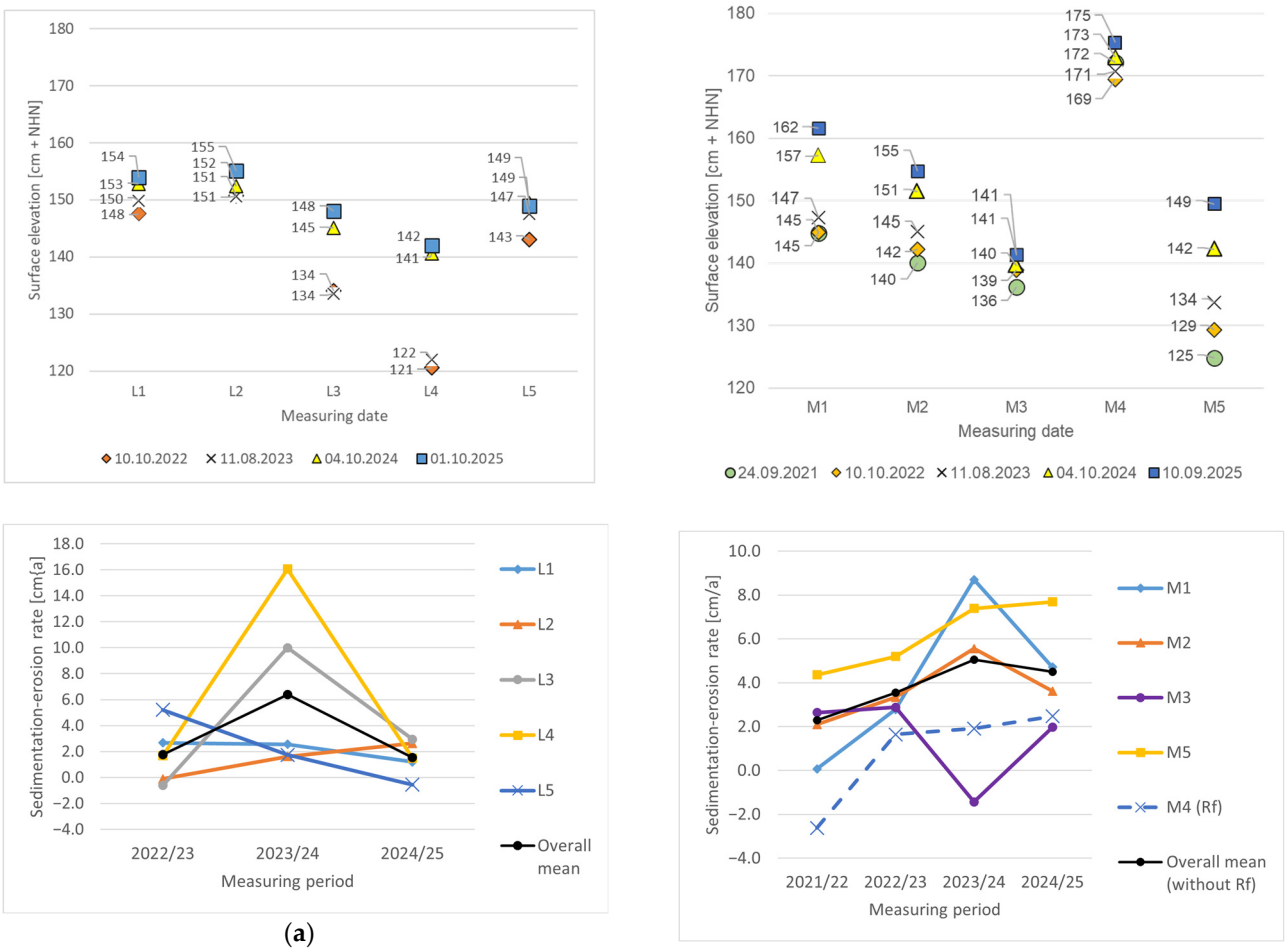
3.1. Surface Elevation Changes

Following topsoil removal, the initial surface elevation at the Leybucht study site ranged from +1.2 to +1.5 m NHN, exhibiting a distinct north-to-south gradient. In the post-construction state, the terrain at the Manslagt site exhibited a flat topography, with variations from mechanical grading ranging between +1.2 and +1.4 m NHN.

3.1.1. Sedimentation–Erosion Bars

The development of the surface height for all SEBs in Manslagt and Leybucht relative to NHN over time and the sedimentation–erosion rates are shown in Figure 6. Over the entire monitoring period from 2021/2022 to 2025, the median annual sedimentation rate measured by the SEBs at the Leybucht site was 3.2 cm/a (ranging from −0.6 to 16.1 cm/a), and 3.8 cm/a (ranging from −1.4 to 8.7 cm/a) at the Manslagt site, excluding the reference SEB. The surface elevation changes over the entire measuring window, showing a cumulative mean sediment accretion of 9.9 cm in Leybucht, and of 15.4 cm in Manslagt (excluding reference SEB). In comparison, the reference SEBs in Manslagt recorded a total cumulative accretion of 3.4 cm, corresponding to an annual rate of 0.9 cm/a.

Interannual variations revealed a pronounced peak in accretion during the 2023/2024 monitoring interval, with mean rates reaching 6.4 cm/a in the Leybucht and 5.1 cm/a in Manslagt, excluding the reference SEB. Conversely, the lowest accretion rates were documented in 2024/2025 for the Leybucht, with a mean of 1.5 cm/a, and in 2021/2022, for Manslagt, with a mean of 2.3 cm/a, excluding the reference SEB.



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

Figure 6. Temporal development of surface elevation [cm relative to NHN], measured during the monitoring phases from 2021/22 to 2025 with SEBs at the study sites (**upper panel**) and sedimentation–erosion rate [cm/a] (**lower panel**): (**a**) Leybucht (**left**) and (**b**) Manslagt (**right**).

3.1.2. Digital Terrain Models

Prior to the restoration measures, the salt marshes in Manslagt and Leybucht were characterized by anthropogenic structures, including grid-like drainage ditches and artificially raised bed structures.

Following the topsoil removal, the surface elevation at both study sites was lowered, resulting in a predominantly flat topography. In Manslagt, only the main tidal creek was imprinted, whereas the Leybucht exhibited a slight elevation gradient toward the north. Figure 7 illustrates the baseline DTMs from November 2020, the subsequent DTMs after four (Leybucht) and five (Manslagt) years, and the resulting digital elevation models of difference depicting sedimentation and erosion rates.

In 2020, the elevation generally decreased from west, with +1.5 to +1.8 m NHN, to east, with the lowest areas situated in the southeast, with +1.0 to +1.3 m NHN. The north-to-south gradient excavation depths of the restoration measure were no longer clearly visible based on the DTMs. In Manslagt, the baseline elevation was mostly between +1.2 and +1.4 m NHN, featuring a gentle upward slope from the low-lying edges of the main creek, with +0.8 to +0.9 m NHN, toward the transition zones of the adjacent, undisturbed areas, with +1.7 to +1.8 m NHN. Just weeks after the completion of the measures, early stages of tidal creek formation were already visible in the DTMs of both areas.

By 2024, the general surface elevation in Leybucht had increased, predominantly ranging from +1.4 to +1.7 m NHN. Notably, the elevation gradient shifted, with the

northern section tending to be lower than the southern area. In Manslagt, extensive areas reached elevations between +1.5 and +1.7 m NHN. After the respective 4- and 5-year monitoring periods, a highly ramified tidal creek network had developed across large parts of both sites. Erosion was exclusively restricted to these creek structures; however, exact erosion depths could not be reliably quantified via DTMs due to signal absorption and errors caused by residual water in the channels.

Distinct morphological features developed along the main creeks and the boundaries to the undisturbed areas, where elevated marsh platforms (natural levees) reached +1.8 to +2.0 m NHN in Leybucht and +1.7 to +1.9 m NHN in Manslagt. Consequently, the transition from the creek edges to the surrounding marsh platform steepened over time, although a gentler gradient persisted in the western sections. In the immediate vicinity of the tidal creeks and adjacent ditches, cumulative sedimentation rates from 2020 to 2024/25 reached over 60 cm in Leybucht and 70 cm in Manslagt. Peripheral areas, particularly in the eastern part of Leybucht, exhibited accretion of up to 30 cm. In contrast, surface elevations remained largely unchanged in the central and northern parts of Leybucht, as well as in the northern and southeastern sectors of Manslagt. Another distinct morphological feature observed in Leybucht, particularly in the northern area, was the presence of linear depressions reminiscent of historical agricultural drainage ditches, which were entirely absent in Manslagt.

The temporal evolution of the elevation distribution within the study areas is presented as cumulative frequency curves in Figure 8. To generate these curves, the DTM data from the monitoring campaigns were classified into 10 cm elevation increments. The area percentage of each class was calculated relative to the total area of the respective study site to derive the cumulative distributions. For the Leybucht study area, certain monitoring campaigns listed in Table 4 were excluded due to incomplete data coverage. For both study areas, the cumulative curves exhibit a pronounced, predominant accretion over the monitoring period, which is clearly indicated by a shift of the curves toward higher elevation classes.

During the observation period, a significant upward shift in the vertical height distribution was observed at both study sites:

In the Leybucht, the surface in 2020 was characterized by lower elevations, with 82% of the total area concentrated between +1.3 m and +1.5 m NHN (43% between +1.3 and +1.4 m NHN; 39% between +1.4 and +1.5 m NHN). By 2024, this distribution had shifted significantly toward higher elevation levels: the +1.3 to +1.4 m NHN class had declined to just 18%, while the higher classes expanded considerably, with +1.4 to +1.5 m NHN accounting for 30%, +1.5 to +1.6 m NHN for 29%, and +1.6 to +1.7 m NHN for 15% of the total area (Figure 7, upper panel).

A comparable shift occurred in Manslagt. While lower levels (+1.2 to +1.5 m NHN) dominated the site in 2020 (accounting for 24%, 36%, and 18%, respectively), pronounced accretion by 2025 elevated the terrain predominantly elevation levels: 31% was located in the +1.5 m to +1.6 m NHN class, 52% in the +1.6 m to +1.7 m NHN class, and 11% in the +1.7 m to +1.8 m NHN class (Figure 7, lower panel).

When interpreting the subsequent surveys, the derived DTMs, and cumulative elevation frequency curves, it should be noted that a residual risk of slightly overestimating surface elevation in densely vegetated areas remains. However, classifying the elevation changes into 10 cm intervals still allows for a reliable interpretation of the elevation models of difference results.

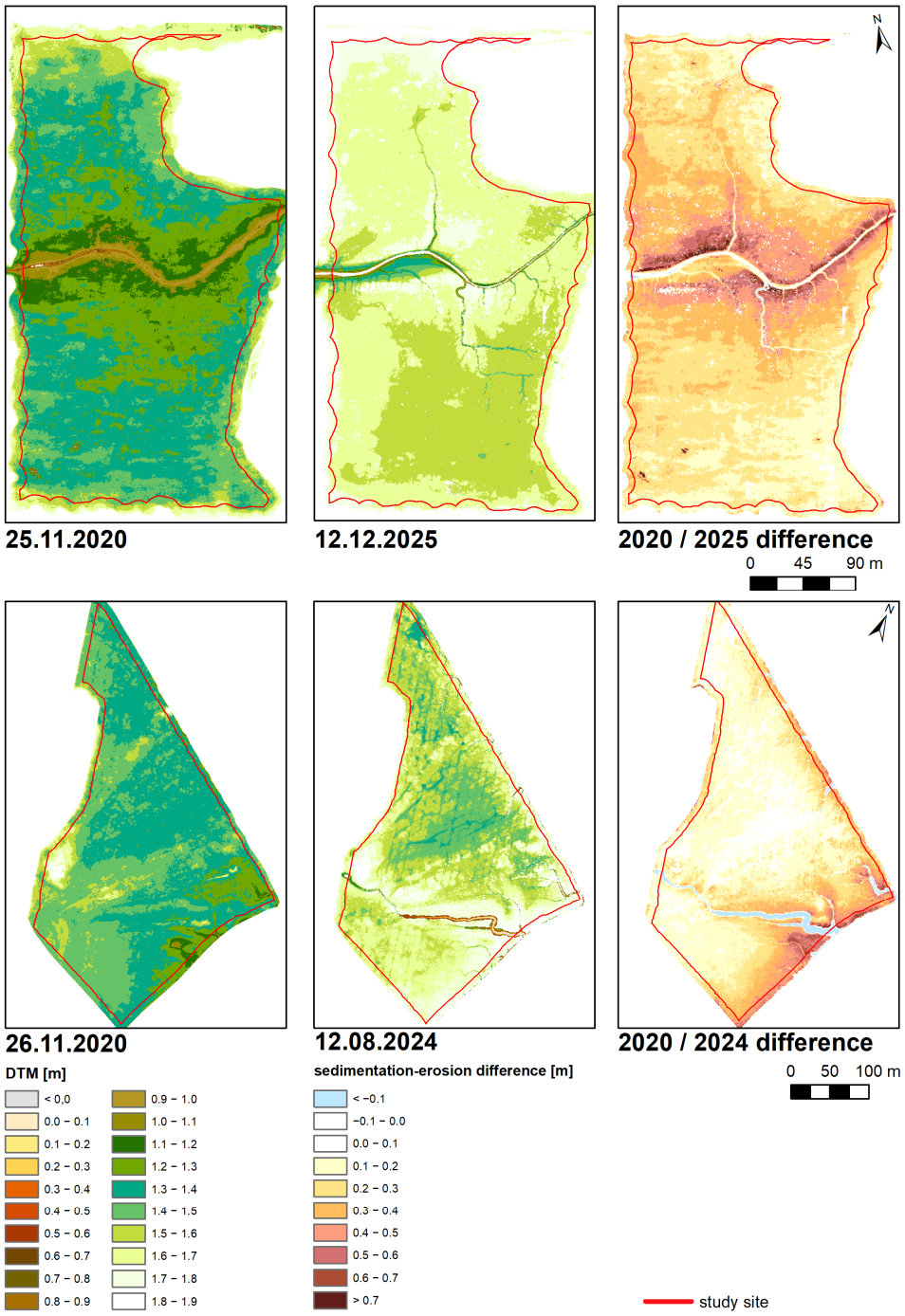


Figure 7. Digital terrain models and differential maps with spatial resolution of 0.1 m showing sedimentation and erosion [m] in Manslagt (**upper panels**) and the Leybucht (**lower panels**) (2020 UAV photogrammetry, 2024/2025 UAV LIDAR). (For details on accuracy, see Table 4 and Section 2.3.1.)

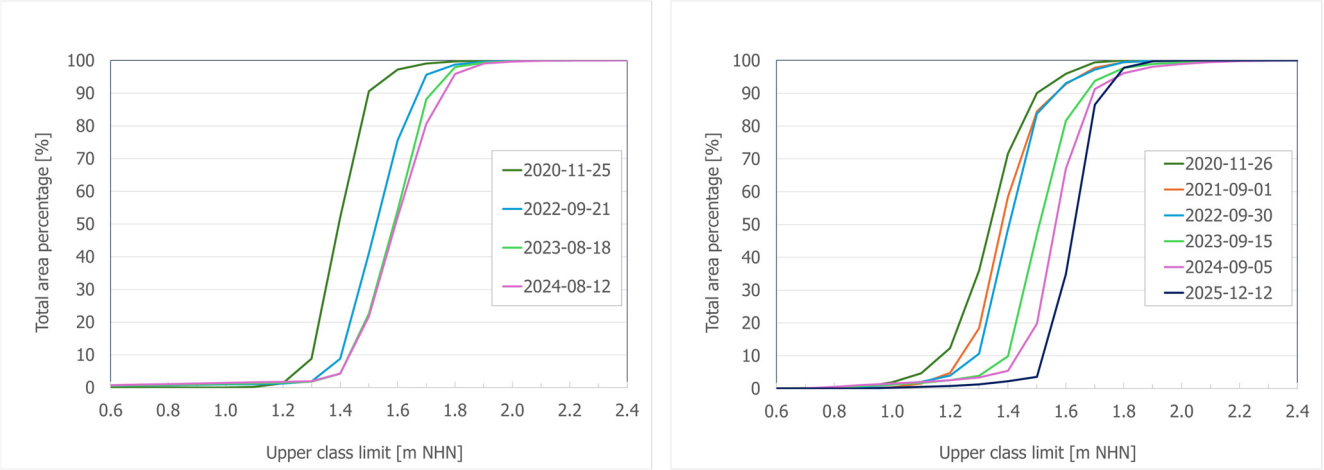


Figure 8. Cumulative elevation frequency curves in 10 cm classes for the Leybucht (**left**) and Manslagt (**right**) study sites derived from digital elevation models. (For details on accuracy, see Table 4 and Section 2.3.1.)

3.2. Morphological Evolution of Tidal Creek Networks

The initial state of the drainage structures across both study areas showed a strong anthropogenic imprint, characterized by a highly uniform, rectangular network of linear, ditches.

Following the completion of the restoration measures, a distinct transition toward natural tidal creek development was observed. In the Leybucht tidal creek development predominantly initiated from the artificial ditches bordering the eastern, northern, and southern margins of the restoration site (Figure 9). At the Manslagt secondary lateral branches developed northward and southward into the excavation area, originating directly from the pre-established main creek designed for dike-foot drainage (Figure 10). The developing creeks exhibit linear to sinuous, dendritic structures (cf. [62]) and have maintained high planform stability over the monitoring years. In one case at the Manslagt site, located shortly upstream of the inlet, the main tidal creek exhibits re-routing tendencies, indicating active dynamic creek avulsion (Figure 10).

In general, both the total length and density of the tidal creeks exhibit a continuous increase over the monitoring period (Table 6, Figure 11). In the Leybucht, the total creek length expanded from approximately 231 m in November 2020 to over 1357 m in August 2024, representing a total net expansion of 1126 m over the almost 4-year observation window. In Manslagt, the total network length increased from around 142 m in November 2020 to 1449 m in December 2025, yielding a growth of 1307 m over the 4-year period. Consequently, network density increased from an initial 30 m/ha in 2020 to 179 m/ha in the Leybucht, representing a 6-fold increase, and from 21 m/ha to 214 m/ha in Manslagt, representing a 10-fold increase (Table 6).

Taking the measurement periods into account, the largest expansion occurs following the implementation of the measure. In the Leybucht, the length increases with an annual growth rate of 181%, although this first interval covers only 143 days in winter. Furthermore, in the Leybucht a second strong expansion phase occurs during 2023 to 2024 with an annual growth rate of 84%. In Manslagt, the length expanded by 92 to 101% per year during the first years. Over the years, these annual expansion rates decline steadily, dropping to 19% in 2024 in the Leybucht, and down to 7% by 2025 in Manslagt.

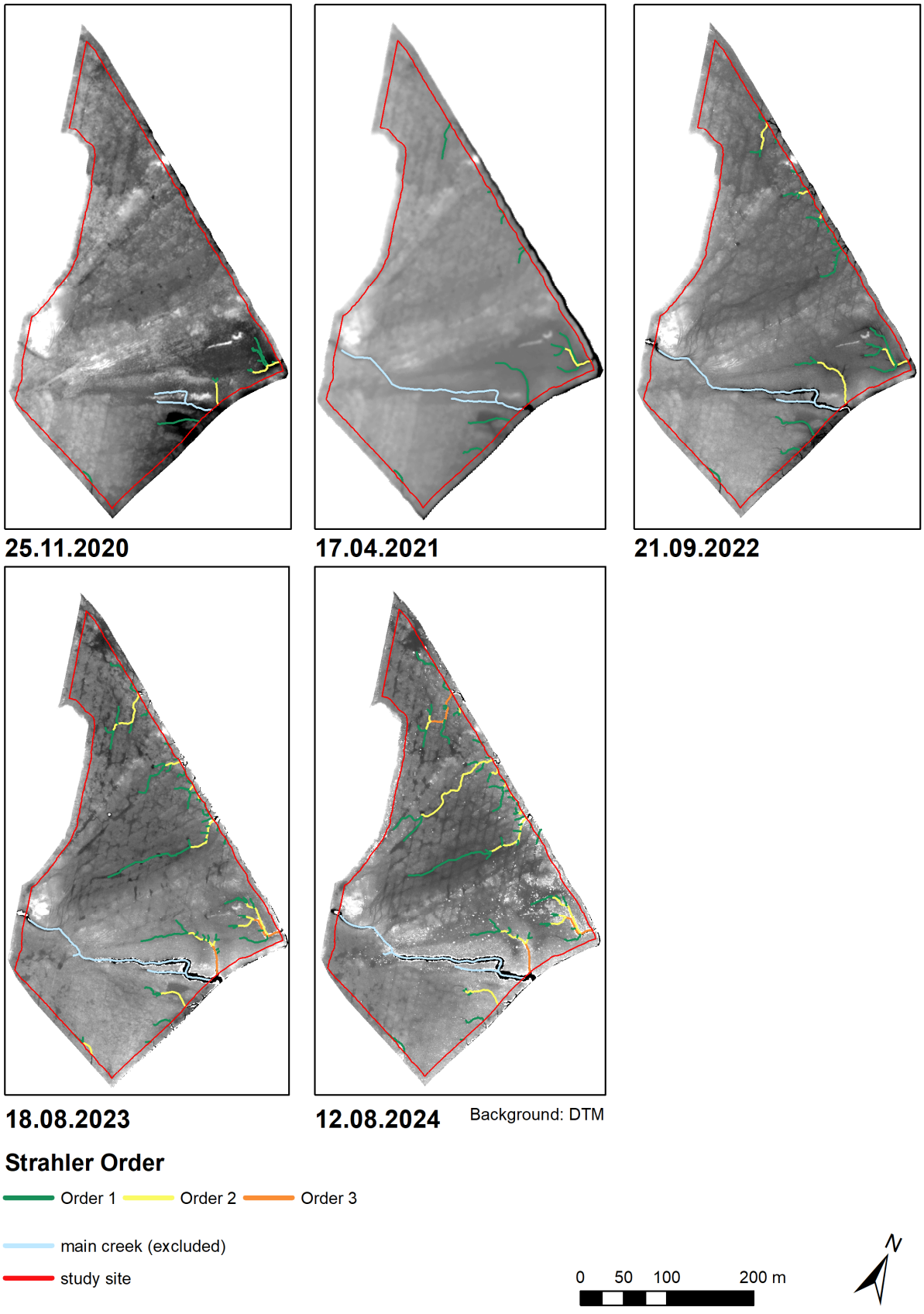


Figure 9. Development of tidal creek structures in the Leybucht in the years 2020 to 2024.

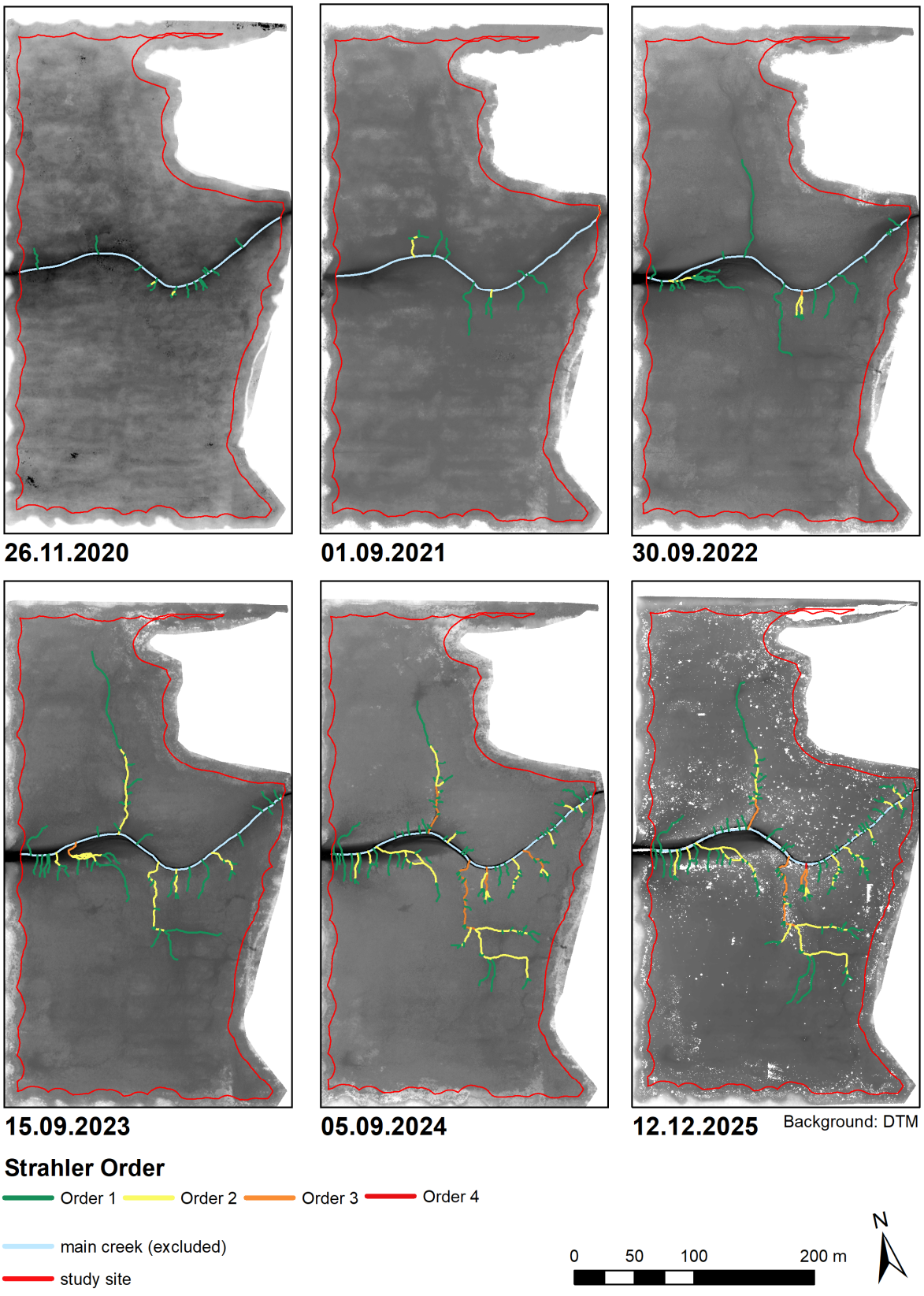
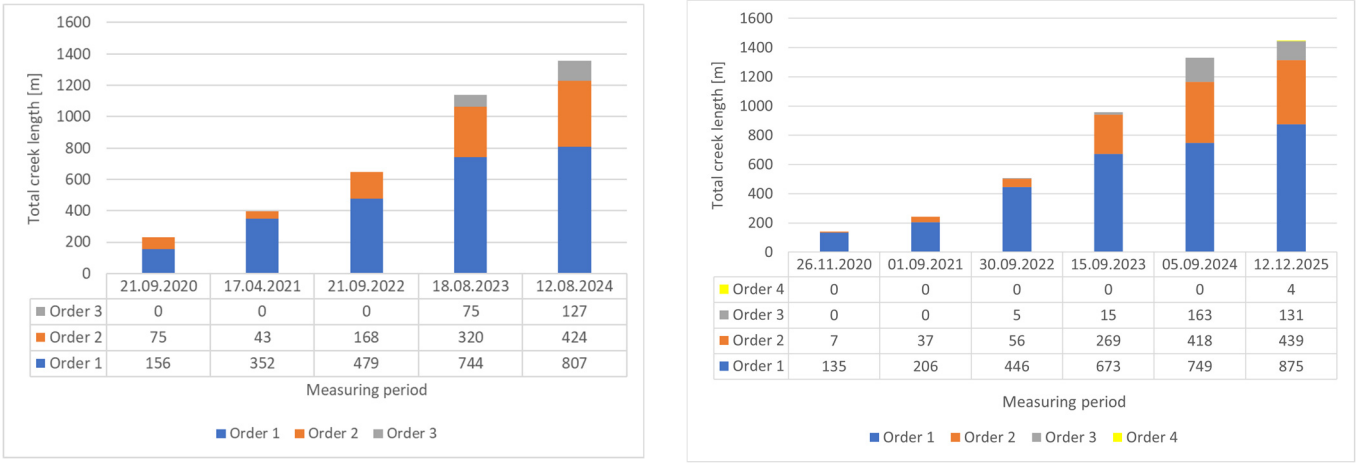


Figure 10. Development of tidal creek structures in Manslagt by measure in the years 2020 to 2025.

Table 6. Temporal evolution of total tidal creek length [m] at the Leybucht and Manslagt study sites from 2020 to 2024/25, excluding main (anthropogenically modified) creeks.

Leybucht				
Survey Date	Time Interval [days]	Total Length [m]	Total Density [m/ha]	Length Growth/ a [%]
25 November 2020	-	231	30	-
17 April 2021	143	395	52	181
21 September 2022	522	647	85	45
18 August 2023	331	1191	150	84
12 August 2024	360	1357	179	19
Manslagt				
Survey Date	Time Interval [days]	Total Length [m]	Total Density [m/ha]	Length Growth/ a [%]
26 November 2020	-	142	21	-
1 September 2021	279	243	36	93
30 September 2022	394	507	75	101
15 September 2023	350	956	142	92
5 September 2024	356	1330	198	40
12 December 2025	463	1449	215	7



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

Figure 11. Temporal evolution of total tidal creek length [m] at the Manslagt and Leybucht study sites from 2020 to 2024/25, excluding main (anthropogenically modified) creeks. (**a**) Leybucht (**left**) and (**b**) Manslagt (**right**) [60].

The general increase in total creek length and density is also reflected in the individual order classes (Figure 11). However, first-order creeks exhibit a decelerating annual growth rate from the start of the monitoring period onward: in Leybucht, starting with 63% in 2020/2021, and dropping down to 9% in 2023/2024; and in Manslagt, starting with 69% in 2020/2021, and dropping down to 12% in 2023/2024. An exception is the second measuring period from 2021/2022 in Manslagt, where an annual growth rate of 152% was measured. In contrast, no clear trend is discernible for the higher-order classes.

At the onset of the monitoring period, the tidal creek network was predominantly characterized by first-order structures (67% in Leybucht; 95% in Manslagt), while higher-order tidal creek structures accounted for 5% (second-order, Manslagt) to one-third of the network (second-order 33%, third-order 0%, Leybucht). By 2024 in Leybucht or 2025 in Manslagt, their collective share increased to over 40% (second-order > 30%; third-order <

10%), whereas the proportion of the first-order structures declined to 50 to 60%. Notably, fourth-order tidal creek segments were documented exclusively in Manslagt in 2025.

The results of the structural analysis using the bifurcation ratio show the following: In the Leybucht in 2024, the network comprised 58 first-order, 15 s-order, and three third-order segments, resulting in bifurcation ratios of 3.9 (order 1 to 2) and 5.0 (order 2 to 3). In Manslagt in 2025, the network consists of 124 first-order, 18 s-order, four third-order, and one fourth-order segments, resulting in bifurcation ratios of 6.9, 4.5, and 4.0 respectively.

3.3. Effects on Conservation Status

Across both study sites, the baseline state of ecological conservation status was assessed as unfavorable–inadequate to unfavorable–bad (B to C), with the exception of certain water pools and salt pans. In the Leybucht, the seaward areas featuring naturally developing salt marshes are rated as favorable (A) [45,51]. This initial assessment is attributed to the presence of anthropogenic drainage structures and a uniform relief characterized by ditches and ridges.

Within a few years of implementing the restoration measure, a near-natural network of meandering tidal creeks developed in both study sites. These structures originated from the pre-existing main tidal creeks and the ditch structures adjacent to the study sites. Consequently, the 'tidal creeks' criterion can now be rated as good (B) to excellent (A) at both sites. Furthermore, the micro-topography along these tidal creek structures features elevated tidal creek banks, isolated vegetation-free depressions, and ridges. Thus, the 'relief' criterion can be rated as good (B) to excellent (A) in both sites (Table 7).

Table 7. Morphological conservation status assessment and classification results from before and after measure implementation. (A, favorable; B, unfavorable–inadequate; C, unfavorable–bad).

Completeness of Habitat-Specific Structures:	Leybucht		Manslagt	
	Before	After	Before	After
Relief	C	B to A	C, exception of some water pools/salt pans featuring B	B to A
Tidal creeks		B to A		B to A

4. Discussion

4.1. Relief

4.1.1. Accretion and Surface Elevation Change

In the Leybucht and Manslagt study sites, the mean sediment accretion rates of approximately 3 to 4 cm/a, measured via SEBs, are consistent with the 3 cm/a transect-derived rates reported for clay pits in Petersgroden [63] and in the southwestern Jade Bay [64]. In the literature, however, these rates only became apparent in the clay pits after the MHW-level was reached. During the initial years after soil excavation, significantly higher sedimentation rates were recorded: up to 15 cm/a at 50 cm below MHW in Petersgroden, and up to +22 cm/a at an average excavation depth of 2 m, which corresponds with an initial elevation ranging from +2.26 m NHN to +2.70 m NHN in various older clay pits in the southwestern Jade Bay [64]. The surface elevation change involving mudflats evolving into salt marshes is typically characterized by a rapid increase until MHW is reached, followed by an equilibrium state [41,65], described as an asymptotic trend [66]. This trend was reported for clay pits [63,64], groyne fields [67], and natural salt marshes, such as in the Scheldt as reported by Temmerman et al. [65]. Since the study sites, Manslagt and

Leybucht, are executed with a base level close to or at the level of the MHW, this trend is less clear here. However, peak sedimentation of 5 cm/a, monitored by SEBs, occurs at +1.30 m NHN near MHW and decreases upward. The spatial distribution of elevations also shows a trend similar to that of the SEBs when comparing the cumulative frequency curves. In the zone at and a few decimeters above the MHW level, the dominant areal proportions in the Leybucht shifted from the elevation classes between +1.3 m and +1.5 m NHN to the classes between +1.5 m and +1.7 m NHN over a 4-year period. Similarly, in Manslagt, the dominant proportions shifted from the elevation classes between +1.2 m and +1.5 m NHN to those between +1.5 m and +1.8 m NHN over a 5-year period. Above MHW, the effects of flooding events appear to be more relevant [64]. A comparison of observation periods reveals higher accretion rates during high storm surge activity [52,53], yielding 5.1 to 6.4 cm/a in 2023/24, than during low-activity intervals, with 1.5 cm/a in 2024/25 and 2.3 cm/a in 2021/22. When comparing interannual accretion rates, potential methodological biases resulting from uneven monitoring periods and seasonal hydrodynamic influences, such as an increased frequency of storm surges in fall and winter, must be taken into account [68]. Consequently, annualized rates derived from shorter periods or periods dominated by storm surges may reflect seasonal peaks rather than long-term steady-state trends. Based on the 4-to-5-year monitoring period, both the Leybucht and Manslagt study site are currently estimated to be in the transition from an early to an intermediate stage [62,69]. This is characterized by rapid vertical accretion and high initial development of creek structures that are gradually decelerating. In the long term, sedimentation rates and terrain elevation are expected to asymptotically adjust to the level of the surrounding salt marshes. Regarding the time scale to reach an equilibrium with the adjacent mature salt marshes, our projected timeline aligns well with long-term observations from older clay extraction sites [63,64]. Specifically, it is estimated that it will take approximately up to 30 years for surface elevation to reach the level of the surrounding salt marshes, which is consistent with the observations by Esselink et al. [70,71] of 14 years and Arens [64] of 30 years. Consequently, Manslagt's accretion rate is expected to stabilize at around 1 cm/a, reflecting both the reference site and the 0.8 to 1.4 cm/a range of more-than-30-year-old Jade Bay clay pits.

4.1.2. Relief Development

On the initially predominantly planar surface, a relief characterized by meandering tidal creeks evolved within the first monitoring periods. This network intensified over time, developing up to four distinct orders. Once established, the spatial positions of these tidal creeks exhibited only minimal migration. This morphological stability aligns with observations by Bartholomä et al. [41] and Arens [64], regarding tidal creek development in clay pits within the Jadebusen.

The geomorphological processes shaping the relief in developing salt marshes are primarily driven by sediment accretion and erosion [72–74]. In the investigated study areas, higher accretion rates occurred predominantly adjacent to the tidal creek systems and along the transition to the surrounding areas (Figures 8 and 9). Along the creek banks, elevation increased up to 60 and 70 cm within four to five years, which corresponds to an average of 12 to 14 cm per year. This spatial pattern is corroborated by the SEB measurements, which recorded the maximum vertical growth at monitoring stations located closest to the tidal creeks, reaching up to 24.6 cm per year at station P5 in Manslagt and 21.4 cm per year at station 4 in the Leybucht. This localized accumulation is driven by the hydrodynamic mechanism whereby suspended sediment is transported through the tidal creeks into the interior areas. The mechanism whereby decreasing water depth, combined with boundary friction, leads to a rapid decline in flow velocity below the critical threshold for sediment suspension is well documented in several three-dimensional modeling

and flume experiments (e.g., [66,75,76]). Arens [64] reported a significantly higher sedimentation rate of 5.6 cm per year at the tidal creek margin compared to rates between 2.2 and 2.6 cm per year measured at interior stations in a nine-year-old clay pit in the Jade Bay.

However, the more rapid vertical growth of up to 60 cm over 5 years observed in the peripheral areas of the study sites cannot be explained solely by proximity to sediment sources, given the distance to the main tidal creek structures. Instead, the accelerated accretion might be driven by the gently sloping topography of the transition zones and the inward migration of vegetation from the adjacent marshes. The terrain surface in these peripheral zones was specially modelled to create a gradual transition between the surrounding salt marshes and excavated areas. Vegetation recolonization typically proceeds rapidly in these zones due to the higher elevation and immediate proximity to seed sources [77]. Extensive vegetation development attenuates hydrodynamic energy, a mechanism well-documented in the existing literature (e.g., [78–80]). For example, Bouma et al. [73] and Steinigeweg et al. [77] documented hydrodynamic feedback loops involving vegetation, showing that spreading pioneer vegetation efficiently dampens hydrodynamic energy and retains suspended sediments, which forms the mechanistic basis for the accelerated vertical sedimentation observed in our peripheral transition zones.

4.2. Tidal Creek Development

Within the investigated areas, tidal creeks developed primarily from the pre-existing drainage structures. In Manslagt, this initiation was driven by the pre-existing tidal creek, whereas in the Leybucht, development originated from the ditches located at the northeastern boundary of the excavated area. During tidal cycles, water regularly flows from the adjacent mudflats into the excavated basins. Depending on localized micro-topographic conditions, the inflowing water either erodes existing substrate or deposits sediment carried in the water column. This hydrodynamic forcing can initiate the formation of tidal creeks [81]. Even minor surface irregularities can concentrate flow, leading to localized velocity increases and elevated bed shear stress, which subsequently induces erosion and forms initial tidal creeks [81–83]. In the areas where topsoil was excavated to elevations of +1.2 to +1.3 m NHN, spontaneous tidal creek initiation took place. This morphodynamical development mirrors the creek evolution observed in clay extraction sites across the Jade Bay [41,64].

Pre-existing topographic features can significantly influence subsequent tidal creek development, as confirmed by Duin and Dijkema [84]. These features include the preformed tidal creek in Manslagt, as well as relict tidal creek structures or remains of artificially created ditches in the Leybucht. In the northern sector of the Leybucht study site, the excavation depth up to +1.4 to +1.5 m NHN appeared insufficient to completely obliterate these legacy structures. To prevent unintended creek alignment along artificial lines, future restoration projects should ensure that historical features are either excavated deeply enough to be fully erased or completely avoided during initial earthworks.

Post-restoration dynamics were initially characterized by a rapid linear-to-dendritic expansion of sparsely branched tidal creeks spread across both study sites with a high initial progradation rate. Over time, the growth rate decelerated, given way to the development of a more extensively branched network, recognizable by the proliferation of second- and third-order tidal creeks. The current system can be classified as a meandering-dendritic network (cf. [62]) and indicates the increasing aging process of the evolving salt marsh. This morphodynamical development is highly consistent with evolutionary stages documented in equivalent coastal settings [63].

The decelerating growth rate indicates the establishment of a dynamic equilibrium, which is driven by constant shear stress [62]. Once developed, the tidal creeks exhibit a

high degree of stability. This morphodynamical persistence has been confirmed by previous studies in similar coastal environments [63,64]. Regarding the Petersgroden clay pit, Bartholomä et al. [63] documented that the tidal creek network, which evolved within two years after completion of the measure, appears to remain relatively stable after more than seven years of observation. This long-term stability is driven by a self-reinforcing feedback mechanism: as hydraulic resistance decreases, flow becomes concentrated, which subsequently amplifies flow velocities within the creeks [69,72]. Concurrently, suspended sediment increasingly accumulates along the tidal creek margins due to a localized drop of flow velocity overtopping the banks, as described before. This process is known to lead to the formation of bank ridges, which promote vegetation growth due to their elevated position and, thus, exert a biostabilizing effect [76,85]. However, morphodynamical changes can still occur, e.g., triggered by storm surge forcing or vegetation establishment. In Manslagt, a localized silting up of well-developed tidal creeks was observed, particularly during the 2023-to-2024 monitoring period. This siltation might be induced by increased vegetation expansion. Arens and Götting [67] reported a similar eco-geomorphological development involving rapid sediment infill and accretion within a brushwood groyne field.

4.3. Impact on Nature Conservation Status

Across both study sites, the baseline morphological conservation status of the salt marshes at the study sites, Manslagt and Leybucht, was assessed as unfavorable–inadequate to unfavorable–bad (B to C) for both the 'relief' and 'tidal creeks' criteria. This initial rating is attributed to a highly uniform topography shaped by anthropogenic drainage structures, which were characterized by artificial ditches and ridges with little to no presence of meandering tidal creeks. Localized exceptions were certain water pools, salt pans and seaward zones within the Leybucht, where naturally developing salt marshes achieved a favorable (A) rating [51].

Following topsoil removal, a near-natural relief characterized by expanding tidal creeks evolved, coinciding with highly variable spatial sedimentation patterns. Tidal creeks with elevated banks formed within a few years of project implementation, covering extensive areas of the study sites. Residual anthropogenic influences, such as the pre-existing main tidal creek in Manslagt and the relict ditch structures in the northern parts of the Leybucht site, remain visible but exhibit active morphodynamical evolution. The newly developed tidal creeks across the study areas display a predominantly meandering planform geometry. Arens and Götting [67] classified salt marshes of the Cappeler Tief established within groyne fields without artificial drainage as close to natural according to standard assessment guidelines [86], noting their near-natural creek systems and corresponding salt marsh vegetation. Additionally, Arens [64] and Bartholomä et al. [63] indicated that geomorphological structures evolving within clay extraction pits closely resemble those formed under pristine, natural conditions. Quantifying the spatial density of the tidal creek systems at both study sites corroborates this development toward natural development. In 2025, drainage densities reached 179 m/ha in the Leybucht and 214 m/ha in Manslagt, which is consistent with natural salt marshes, such as documented densities of 205 m/ha in Schleswig-Holstein [87] and 233 m/ha in England [59]. In addition, the bifurcation ratios (R_b = 3.8–6.9) exceed the benchmark of 3.5 established in the literature for mature, natural salt marshes [88,89]. The present values reflect a salt marsh in transition, characterized by a high number of first-order segments. As observed by Chirol et al. [89] in young managed realignments, the network is expected to slowly consolidate over the coming decades through sedimentation and the merging of lateral channels, evolving toward a natural equilibrium.

In conjunction with the evolving relief and its micro-scale depositional patterns, these findings allow for a comprehensive assessment of the morphological conservation status. Taking both the 'relief' and 'tidal creeks' criteria into account, the current state and anticipated natural development of both study sites exhibit distinct aspects of a favorable (A) rating, despite exhibiting localized 'unfavorable–inadequate' (B) aspects related to the persistent remnants of anthropogenic structures.

5. Conclusions and Outlook

This study demonstrates that topsoil removal in anthropogenically influenced or artificially elevated foreland salt marshes is an effective measure to initiate near-natural dynamic morphological development. A critical prerequisite for initiating such development is lowering the soil to an elevation below the MHW level. Regular tidal inundation exposes the site to natural hydrodynamic forces, driving sedimentation and erosion patterns that form meandering tidal creek networks, which are the foundation for natural vegetation development. In contrast, previously trenched salt marshes following agricultural abandonment [64] or managed realignment sites [59] rarely exhibit the spontaneous formation of natural drainage systems. This morphological stagnation is mainly attributed to permanent changes in soil structure and composition due to anthropogenic disturbances [90]. Therefore, complete physical removal of these compacted anthropogenic structures is essential to induce the natural succession of pioneer and lower salt marsh stages. Based on the monitored sites, an excavation depth of at least +1.20 to +1.30 m NHN (=10 cm below MHW) appears successful for promoting these dynamic processes. While this approach enables near-natural creek evolution, comprehensive planning must carefully account for the spatial distribution and elevation of anthropogenic structures, as these can influence local hydrodynamics. It should be noted that the depth recommendation of +1.20 to +1.30 m NHN (=10 cm below MHW) applies specifically to mesotidal Wadden Sea areas with comparable availability of suspended sediment. In habitats with lower concentrations of suspended sediment, an initial surface elevation closer to the MHW should be aimed for, or the removal of sediment should be reconsidered as an appropriate measure, whereas a higher availability of suspended sediment would allow for slightly deeper excavation depths. Furthermore, regional variations in tidal range would influence the absolute elevation thresholds, as the zoning depends directly on the local tidal range.

Looking forward, this restoration strategy offers substantial co-benefits for nature conservation, as well as for climate-change mitigation and adaptation. Globally, salt marsh restoration is estimated to have the potential to offset up to 0.51% of annual energy-related CO_2 emissions through enhanced carbon sequestration [91]. Within the regional context, initiatives such as the Blue Carbon project confirm that measures like topsoil removal and the opening of summer dikes have high Blue Carbon potential [32]. The restoration of natural tidal dynamics is particularly important here, as waterlogged soil conditions limit aerobic decomposition, thereby maximizing the burial and preservation of organic carbon [92]. At the same time, the excavated clay provides suitable material needed for coastal protection measures, such as dike reinforcements, directly contributing to adaptation strategies for CFERM against accelerating sea-level rise.

However, the shifting boundary conditions driven by climate change—including alterations in mean sea levels, tidal ranges, and wind regimes—require adaptive management strategies [13]. As recommended by Bartholomä et al. [63], future site selection and the planning of topsoil removal or clay extraction pits should be based on high-resolution, small-scale hydrodynamic modeling. This will ensure that these NBSs remain resilient and continue to deliver vital win-win synergies between ecological restoration and coastal flood risk management in a rapidly changing environment.

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