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Creek systems in restored coastal wetlands: Morphological evolution and design implications

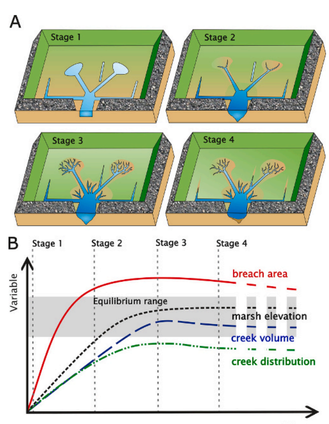
C. Chirol[a,b,*], N. Pontee[c,a], S.L. Gallop[d,e], C.E.L. Thompson[a], H. Kassem[a], I.D. Haigh[a]

[a] School of Ocean and Earth Sciences, National Oceanography Centre Southampton, University of Southampton, Southampton SO14 3ZH, UK
[b] Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, 91120 Palaiseau, France
[c] Jacobs, Bristol BS2 0ZX, UK
[d] School of Science, University of Waikato, Tauranga 3110, New Zealand
[e] Environmental Research Institute, University of Waikato, Hamilton 3240, New Zealand

HIGHLIGHTS

- Impacts of creek design on restored saltmarsh evolution are poorly understood.
- We monitor 10 restored creek systems in the UK over 2–20 years using lidar.
- External and internal conditions determine ability for creek evolution.
- Restored creeks are poorly distributed compared to natural systems.
- We propose updated guidance for creek network design and implementation.

GRAPHICAL ABSTRACT



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ABSTRACT

Saltmarsh restoration such as managed realignment (MR) projects often include excavation of simplified tidal creek networks to improve drainage and marsh functioning, but their design is based on limited evidence. This paper compares the morphological evolution of creek networks in current MR projects in the UK with creek networks in natural saltmarshes, in order to provide improved guidance.

The evolution of creek networks was monitored for 2–20 years post-breach at 10 MR sites across the UK by semi-automatically extracting 12 morphological creek parameters from lidar. The rates of creek evolution in MR sites are linked to the initial tidal, morphological and sedimentological conditions using principal component

Abbreviations: CSA, Total mouth cross-sectional area; D, Main channel mouth depth; DD, Drainage density; MCG, Main channel gradient; MCL, Main channel length; MR, Managed realignment; MWS, Mean elevation above mean spring level; NB, Number of creeks; OPL, Overmarsh path length; PA, Planform area; PCA, Principal Component Analysis; SR, Sinuosity ratio; TCL, Total channel length; TP, Tidal prism (creek volume).

* Corresponding author at: Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, 91120 Palaiseau, France.

E-mail addresses: clementine.chirol@inrae.fr (C. Chirol), Nigel.Pontee@jacobs.com (N. Pontee), shari.gallop@waikato.ac.nz (S.L. Gallop), celt1@noc.soton.ac.uk (C.E.L. Thompson), hachem.kassem@soton.ac.uk (H. Kassem), I.D.Haigh@soton.ac.uk (I.D. Haigh).

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Morphological equilibrium
Morphometry

analysis, then compared with power law relationships of morphological equilibrium defined from 13 mature natural saltmarshes.

MR creeks evolved into larger, more complex, better distributed systems, with a total creek length and volume statistically similar to their natural counterparts. However, the creek volume remains poorly distributed, with a mean distance between creeks ranging from 33 to 101 m versus 5–15 m for natural mature saltmarshes. MR creeks are also clustered around the breach area, leaving the marsh interior poorly drained. MR creek network morphologies remain strongly influenced by the initial creek template, as evidenced by unnaturally straight creeks inherited from former drainage ditches.

A combination of external conditions (i.e., tidal range, sediment concentration in the wider estuary) and local conditions (i.e., site elevation, topographical heterogeneity, soil compaction) controls how easily creeks can form within MR sites. This in turn determines the amount of engineering effort required to help achieve reference site conditions. The end goal of creek design is to create MR sites that closely resemble reference site conditions, however the final design is also likely to be affected by a range of practical factors (e.g. engineering/cost) unique to each site and project.

1. Introduction

Saltmarshes provide a wide range of benefits to society (Luisetti et al., 2014), such as reducing coastal flooding and erosion (Kirwan et al., 2016), improving water quality (Nelson and Zavaleta, 2012), and trapping carbon from the atmosphere (Macreadie et al., 2013). In order to compensate for historical losses (Lotze et al., 2006) and the ongoing impacts of sea-level rise and coastal urbanisation, restoration projects are being implemented worldwide. Among these, managed realignment (MR) projects aim to restore saltmarsh and mudflat habitats by moving the existing line of defence landward and breaching the old flood defence to restore reclaimed land to tidal influence.

A key determinant of MR success is the implementation of an appropriate pre-breach morphology to kick-start the natural physical processes that allow saltmarshes to evolve towards a mature, stable state (Cooper et al., 2004; Leggett et al., 2004; Palmer, 2009). The number and dimensions of breaches, site elevation and initial creek network all impact the hydrodynamics and thus morphological evolution of the site.

Creek networks are crucial to the ecological stability of wetlands and to saltmarsh restoration planning (Hood, 2020). Their morphology and spatial distribution are relevant to various saltmarsh processes such as sediment transport (Ortals et al., 2021), marsh flow attenuation (Kiesel et al., 2020), seed dispersal (Shi et al., 2020), development of vegetation patches (Taramelli et al., 2018; Wu et al., 2020), fish use (Burgess et al., 2020), and carbon storage (Tan et al., 2020). In natural systems, creek networks develop spontaneously through both depositional and erosional processes as the wetland transitions from mudflats to saltmarshes, in a process expected to take place over a multidecadal to century scale (Chirol et al., 2018; Steel, 1996). In natural settings, saltmarshes tend to evolve from the vertical accretion of mudflats (Allen, 1995; Pethick, 1992; Steel and Pye, 1997). The elevation of MR sites prior to realignment varies with different sites containing variable proportions of low-lying areas suitable for mudflat development and higher areas suitable for saltmarsh development.

The capacity of creeks to initiate and evolve unassisted in the higher areas is uncertain. Therefore, recent MR projects often include artificially excavated creeks designed to accelerate creek development and saltmarsh evolution. The aim is to hasten a mature state in equilibrium with the tidal forcings of the wider estuary, and meet target conditions for habitat restoration (Crooks et al., 2002; Wallace et al., 2005).

The generally accepted guidance is that the artificially excavated creek networks should mimic the morphometric properties of nearby natural mature systems, i.e., reference sites (Pontee et al., 2021, Chapter 5). Based on this principle, several equilibrium relationships have been established linking the creek volume and cross-sectional area of the outlet, the total channel length to marsh area, and the marsh elevation to mean distance between creeks (Chirol et al., 2018; Steel and Pye, 1997). Observations of natural, mature system creeks have also led to quantitative guidance for morphometric properties such as the junction angle, bifurcation ratio, sinuosity and drainage density, detailed in Table 1. A maximum distance between creeks of 30 m has been repeatedly recommended to ensure a good repartition of drainage (Haltiner and Williams, 1987; Larson et al., 2018).

Given the relatively high costs associated with creek network excavation, it is crucial to determine the minimal amount of site preparation needed to kick-start natural creek development processes. A large variety of initial designs have been used in the UK over the past 20 years

Table 1
Summary of existing guidance for the excavation of creek networks in saltmarsh restoration projects.

Factor	Existing guidelines	Date recorded
Initial marsh elevation	Initial marsh elevation should be about MHWS-0.50 m to promote depositional processes (Burd, 1995). Slope should be added to the marsh surface to encourage drainage (Williams and Faber, 2004)	1995
Total creek volume	The creek volume should be at equilibrium with the potential tidal prism to prevent sediment infill, erosion or poor water circulation (Haltiner and Williams, 1987). Equilibrium relationships relate creek volume to the total discharge (Haltiner and Williams, 1987) and outlet cross-sectional area (Steel and Pye, 1997).	1987
Channel length	Channel length per creek should be a function of the creek order following Horton's power laws of channel length decrease with increasing Strahler order (Coats et al., 1995).	1995
Channel cross-sectional dimensions	Channel width and depth should obey hydraulic geometry relationships, and have similar width/depth ratios as natural systems (Zeff, 1999).Cut creeks should not be too narrow since gradual slopes are needed for fish to move between the creek network and the marsh (Dixon et al., 2008)	1999
Bifurcation ratios	Bifurcation ratios should be approximately 3.5 as in natural systems (Coats et al., 1995).	1995
Junction angle	Slough junctions should be about 120 degrees, and channel junctions with sloughs at about 90 degrees to imitate natural systems (Haltiner and Williams, 1987).	1987
Sinuosity ratio	The mean sinuosity ratio should range between 1.1 and 2.0 for Strahler orders 3–5 to imitate natural systems. Smaller channels will tend to be straighter (Coats et al., 1995).	1995
Drainage densities and distribution	Drainage density should be similar to that of nearby reference saltmarshes (Williams and Faber, 2004). Maximum distance between creeks should be about 30 m (Haltiner and Williams, 1987).	1987
Inherited structures	Inherited structures like drainage ditches should ideally be infilled to prevent overly straight channels (Williams and Faber, 2004).	2004

(Pontee, 2015a), ranging from simple linear distribution channels to more complex configurations mimicking mature creek network morphologies. In order to improve the science-base of future MR design, the effects of these various design choices on creek evolution towards the natural equilibrium state need to be assessed through multiannual monitoring of creek evolution that systematically measures morphometric parameters. Recent progress in semi-automated segmentation and parametrisation of creek morphology from lidar data has enabled the production of time-series of creek evolution in several MR sites in the UK (Chirol et al., 2018, 2022).

The aim of this paper is to explore how creek networks evolve in MR sites depending on their initial conditions and design choices, and how well they mimic natural systems, in order to improve creek design. This is achieved through 3 objectives as follows:

(1) to examine rates of creek morphological evolution from time-series of creek morphological parameters since MR implementation, and links with environmental conditions and MR design choices;
(2) to compare the evolving morphologies of MR creek networks with the equilibrium state found in mature natural saltmarshes and infer a conceptual evolution model; and.
(3) to assess how well existing guidance has been followed and identify key lessons for future design.

2. Study sites, datasets and methods

2.1. Study sites

This study considers 10 MR sites (Abbots Hall, Alkborough, Allfleet, Chowder Ness, Freiston, Hesketh Out Marsh West, Paull Holme Strays, Steart, Tollesbury and Welwick), implemented between 1995 and 2014 around the coast of England (Fig. 1). Sites are selected based on data availability and to include a spectrum of: (1) environmental settings based on initial, external conditions including tidal range, size, breach date, suspended sediment concentration entering the site, land use history and sediment properties; and (2) implementation design (i.e., number and size of breaches, initial site elevation within the tidal frame, targeted habitats, initial creek network design). The sites span tidal ranges of 4.1–11 m, granulometries from clay to coarse silt / sand, suspended sediment concentrations from 60 to 1000 mg/L, mean elevations from 0.9 to 5.5 m above Mean Water Spring, and scheme areas between 0.1 and 3.61 km^2. Detailed site descriptions of each MR project are provided in Chirol et al. (2018b).

Thirteen natural saltmarshes (Banks, Crossens, Gibraltar Point, Grange, Hen Hafod, Longton, Newton Arlosh, Portbury Wharf, Shell Ness, Stiffkey, Tir Morfa, Tollesbury, Warren Farm), representing a range of environmental settings and considered to be in dynamic equilibrium with tidal forces were used as an end-goal for creek morphology in this study. These sites are considered to be representative of natural mature saltmarshes in that they are not significantly affected by human activity, receive no terrestrial water discharge, are aged from 50 to over 2000 years, and have been morphologically for over 20 years. Detailed analysis of these sites and their creek networks are provided by Chirol et al. (2018), Chirol (2018) and Steel (1996).

2.2. Datasets

The evolution of tidal creek networks was assessed using: (1) lidar data collected between 2002 and 2016 by the Environment Agency (EA) accessible via the DEFRA Data Services Platform at a vertical resolution of 0.15 m and a horizontal resolution of 1 m (Environment Agency Defra DSP, 2019)); and (2) and tidal data obtained from the Admiralty Tide Table 2014. Digital Surface Models (DSM) were used instead of Digital Terrain Models (DTM) because the latter did not remove the systematic bias caused by low, dense saltmarsh vegetation (Chirol et al., 2018). Furthermore, the EA proprietary filtering algorithm caused inconsistent patterns of correction between years (Leung, 2017), making the DTM datasets inappropriate for monitoring inter-annual morphological changes. Using DSM datasets assumes that the low vegetation cover characteristic of saltmarsh areas is unlikely to mask the creek network or significantly affect the detection of creek edges.

The following mean tidal levels were interpolated for each site following the approach described in Chirol et al. (2022): Highest

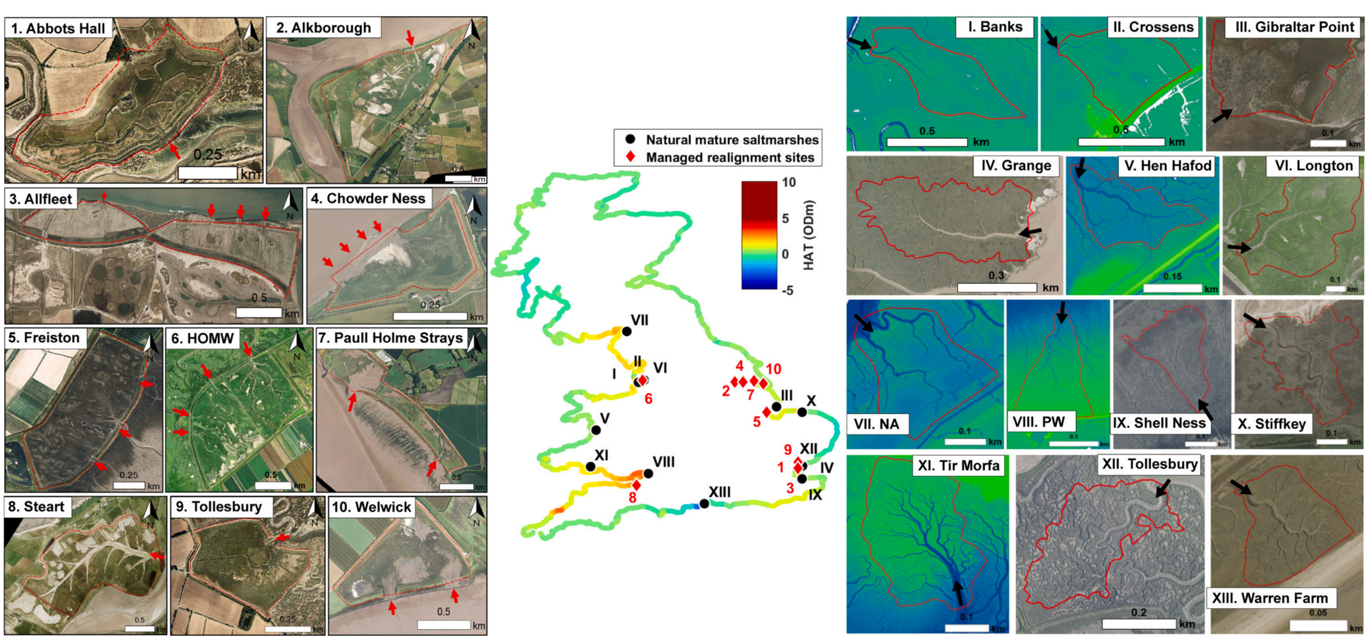

Fig. 1. Location and aerial photography of the 10 MR sites and 13 equilibrium saltmarshes considered, superimposed on the Highest Astronomical Tide (HAT), interpolated along the British coastline from Admiralty Tide Tables 2014 mean predicted tidal levels. On the left, red lines are catchment areas delimited by the remaining seawalls and HAT levels. Red arrows are breach areas. On the right, red lines are catchment areas delimited by HAT levels and the half-distance to the neighbouring creek systems. Black arrows are entry channels connecting the creek network to the wider estuary. HOMW = Hesketh Out Marsh West. NA = New Arlosh. PW = Portbury Wharf.

Astronomical Tide (HAT), Mean High Water Spring (MHWS), Mean High Water Neap (MHWN), Mean Low Water Neap (MLWN), and Mean Low Water Spring (MLWS). We also defined Mean Water Spring (MWS) as the mean between MHWS and MLWS. Available sediment data were obtained from the Water Quality Archive (WIMS) Open Data Portal (Environment Agency WIMS, 2019). For each MR site, the mean particle size and water turbidity of the wider estuary were interpolated using a weighted mean of the available data points as a function of their distance from the MR site. The location and context of MR and their raw tidal and sedimentological data are provided in Appendix 1.

2.3. Creek network extraction and parametrization

Morphometric creek parameters were extracted systematically from all available lidar datasets using a semi-automated algorithm detailed in Chirol et al. (2018a). In brief, creeks were segmented based on elevation and slope thresholds found through sensitivity testing (Appendix 2). A creek network was defined as a connected linear feature at lower elevation than the rest of the saltmarsh, and whose edges are delimited by a steeper slope. The algorithm then performed a morphometric analysis of the creek system to extract a number of creek parameters listed in Table 1. At MR sites containing more than one breach, the main channel was defined as the longest channel connected to the largest outlet, and the mouth cross-sectional area as the sum of all outlets. The creek morphology datasets extracted for the 10 MR sites are provided in a data descriptor (Chirol et al., 2022).

2.4. MR creek evolution rates and relation to creek-forming processes

Evolution rates for MR creeks were estimated for each site from a linear regression fit tested at a 95 % confidence interval for all the normalized parameters listed in Table 2. Residuals from the linear regression were statistically analyzed to determine whether the linear evolution rates exceed the inter-annual variations in creek morphology, and hence whether creek parameters follow a trend or fluctuate around a mean value. If the linear evolution rate is inferior to the mean of the residuals, the creek parameter is considered to fluctuate around a mean value. If the linear evolution rate is >50 %, 68 % or 95 % of the residuals, this is interpreted as the creek parameter following a trend, with greater confidence with increasing percentages. The evolution rates were normalized by their initial parameter to compare sites of various sizes, and expressed as a percentage change per year.

In order to explore which initial conditions of the MR sites accounted for most of the variability in rates of creek morphological evolution, a principal component analysis (PCA) was performed. PCA assumes that all variables are normally distributed, and while this condition is not necessarily met in this study, useful descriptive information can still be inferred in terms of classification of intercorrelated parameters (Jolliffe, 2002). Table 2 shows the variables selected for the PCA analysis:

In order to test whether the principal components (PCs) represent real axes of variation rather than random directions, 1000 non-correlated datasets were generated using a permutation method, and PCs derived for each dataset (Camargo, 2022). A one-sample t-test was then applied to test whether the percentages of variability explained by the first PCs in the permuted datasets have a mean value significantly different from the original dataset. If the real PCs explain a greater percentage of variability than the ones obtained with the permutation method, they can be considered to represent real axes of variation.

Table 2

Creek morphological parameters used in the analysis and uncertainty linked to the creek detection algorithm. The uncertainty is calculated as the standard deviation of morphological parameters detected by the algorithm using Hesketh Out Marsh West as an example when the elevation thresholds are changed by +/− 0.15 m. The percentage value in brackets corresponds to the relative uncertainty, normalized by the mean value of the morphological parameter. Originally from Chirol et al. (2022).

Creek morphological parameters considered in this study	Symbol	Uncertainty (Relative uncertainty in %)
Mean elevation above mean spring level (%/yr)	MWS	N/A
Drainage density (%/yr)	DD	0.5 (5 %)
Overmarsh path length (−%/yr)	OPL	5.08 (11 %)
Main channel length (%/yr)	MCL	36.8 (3 %)
Total channel length (%/yr)	TCL	800 (5 %)
Number of creeks (%/yr)	NB	21.2 (9 %)
Total mouth cross-sectional area (%/yr)	CSA	4.98 (4 %)
Main channel mouth depth (%/yr)	D	0.33 (12 %)
Planform area (%/yr)	PA	$3.49*10^4$ (20 %)
Tidal prism (creek volume) (%/yr)	TP	$2.02*10^4$ (17 %)
Sinuosity ratio (%/yr)	SR	0.07 (6 %)
Main channel gradient (%/yr)	MCG	0.05 (4 %)

2.5. Comparison with the equilibrium morphology of natural saltmarshes

Creek networks in mature saltmarshes have been shown to obey the same morphological principles, represented by morphometric power-laws between creek network morphology (e.g., total channel length) and overall marsh morphology (e.g., catchment area), regardless of their regional location (Chirol et al., 2018; Steel, 1996). These power-laws can be used as a reference to verify whether MR creek networks evolve towards a morphological equilibrium state similar to that of natural mature systems, or whether a new conceptual model of MR creek network evolution should be defined.

Time-series of MR creek morphologies since site implementation were compared with the equilibrium power-laws of natural creek systems defined for 13 mature saltmarshes (Chirol et al., 2018; Steel, 1996). Creek networks in MR sites at their early (< 2 years) and later stages of evolution (> 5 years) were also compared with natural creek systems using a non-parametric Kruskal-Wallis (KW) test of ranks at a 95 % confidence interval for the following creek parameters: planform area normalized by the catchment area, creek volume normalized by the catchment area, drainage density and overmarsh path length. Comparison between natural and restored saltmarshes was also performed for each creek order for the following parameters: number of creek segments, mean length, bifurcation ratio, junction angle, sinuosity ratio, cross-sectional area, width, depth, width/depth ratio and creek volume. This study uses the Reverse Strahler order nomenclature, where Order 1 corresponds to the outlet and each branching then leads to an increase in Order (Chirol et al., 2018). Gibraltar Point and Crossens sites were excluded from the natural mature creek network dataset due to their comparatively younger age (~50 years) and poorly distributed creek networks (Chirol et al., 2018). MR sites Paull Holme Strays, Tollesbury and Steart were also excluded from the natural-MR creek comparison, since the available lidar data did not capture both the early (≤2 years) and later (≥5 years) stages to reliably estimate their evolution. Therefore, 11 natural and 7 MR sites were compared to infer general conclusions on the evolution of MR creeks compared to natural systems.

Finally, the topographical heterogeneity (similar to rugosity and defined here as the small-scale topography measurable over a $50*50\ m^2$ window (Lawrence et al., 2022)) of MR sites was compared with that of the mature natural saltmarshes. The small-scale topography is expected to play an important role in the development of the creek network by creating preferential flow routes (D'Alpaos et al., 2007) and affect saltmarsh ecological functioning by creating a greater range of tidal inundations and drainage conditions (Callaway, 2005). The topographical heterogeneity was extracted from 365 data points over a $50 \times 50\ m^2$ window in the lidar data for each year. The relative positions of the sampling points follow a systematic grid sampling method previously tested in both natural and MR saltmarshes (Brooks et al., 2015; Lawrence et al., 2022).

3. Results

3.1. Morphological evolution rates of MR creek networks

Almost all the MR sites considered have accreted vertically since implementation (Fig. 2). Abbotts Hall, Allfleet and Tollesbury started out predominantly at the elevation of a mudflat (below MLWN) and 8 to 12 years after breaching have not yet reached the elevation of a lower marsh (between MLWN and MHW). However, areas that began at the elevation of a lower marsh (Paull Holme Strays, Chowder Ness, Welwick, and parts of Alkborough and Freiston) have risen to middle-upper marsh elevation levels (above MHW) 6 to 9 years after breaching. Evidence of erosion within the creek networks is observed at Hesketh Out Marsh West, Steart and Freiston, mainly concentrated near the largest breach.

Marsh build-up is accompanied by an increase in creek planform

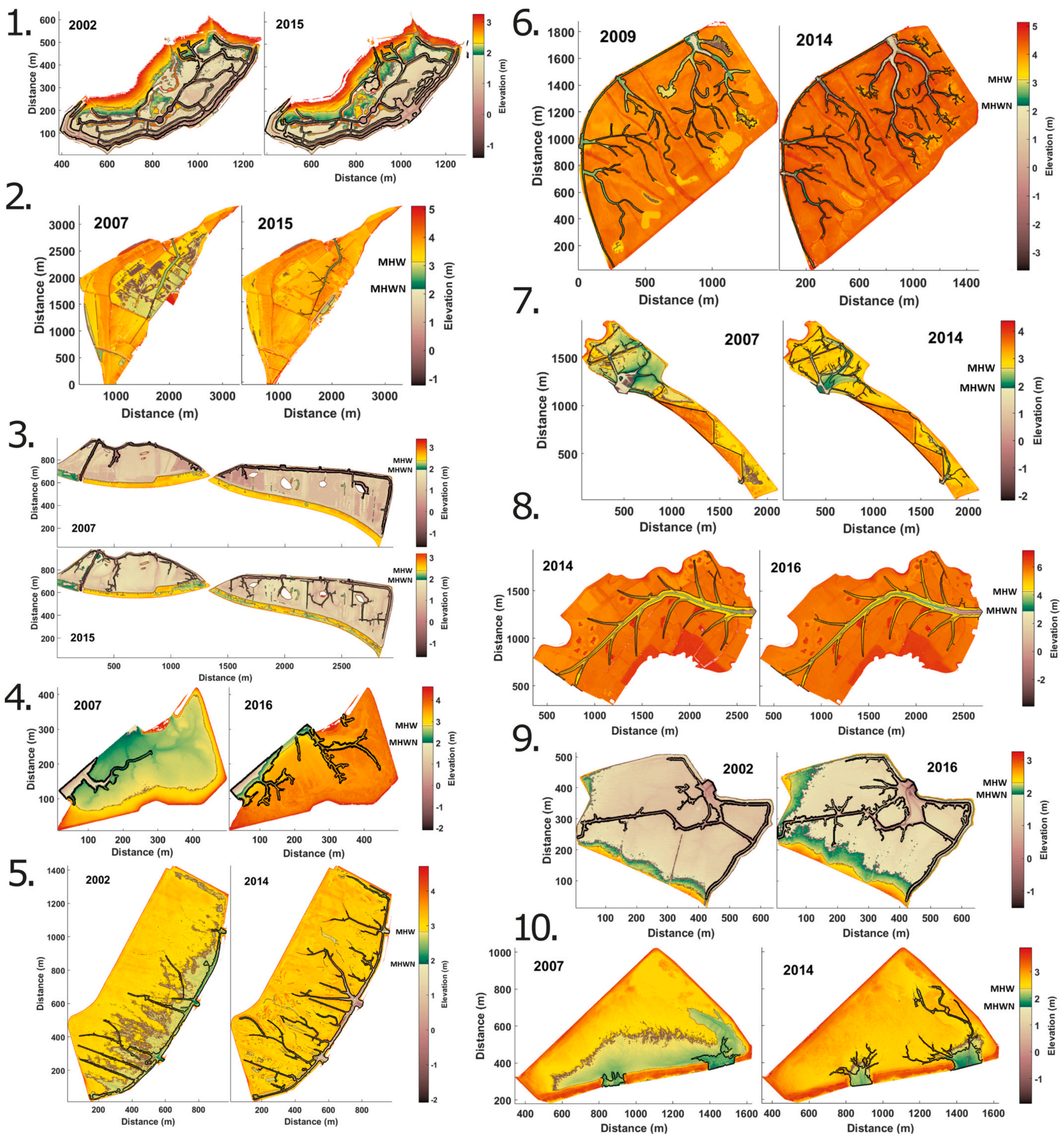

Fig. 2. Elevation changes and creek network evolution in all MR sites through a comparison of the first and last year of lidar monitoring: (1) Abbots Hall, (2) Alkborough, (3) Allfleet, (4) Chowder Ness, (5) Freiston, (6) Hesketh Out Marsh West, (7) Paull Holme Strays, (8) Steart, (9) Tollesbury and (10) Welwick. The black lines show the extent of the creek network planform area as detected by the Chirol et al. (2018) algorithm. The shifts in color scales show the transition between the elevation ranges of the mudflat (below MHWN), the lower marsh (MHWN – MHW) and the middle-upper marsh (above MHW).

area, volume, and distribution over the marsh surface. Different processes appear to drive the initiation of new creeks: reactivation of straight drainage ditches (Alkborough, Allfleet, Freiston), differential accretion based on initial topographical heterogeneities (Chowder Ness, Welwick), headward erosion (Freiston, Welwick), branching out of new creeks on channel bends and accretion within headward ponds (Hesketh Out Marsh West). A summary table of creek morphological parameters at each timestep is provided in Appendix 2.

There is a near-linear increase in total channel length and number of creek segments at all sites (Fig. 3E-F, Table 3). The overmarsh path length decreases at all sites, indicating decreasing mean distance between creeks within each site. The normalized trends derived from linear fits of each parameter in time are a first approximation only — less than half are significant at a 95 % confidence interval (Table 3). Nevertheless, at the timescale considered, the linear evolution rate remains a useful simplified representation of the creek network behaviour, provided that the linear trend supersedes the inter-annual variability of the creek parameters. The linear trend is >50 % of the residuals in 93 % of cases, and >95 % of the residuals in 84 % of cases (Table 3).

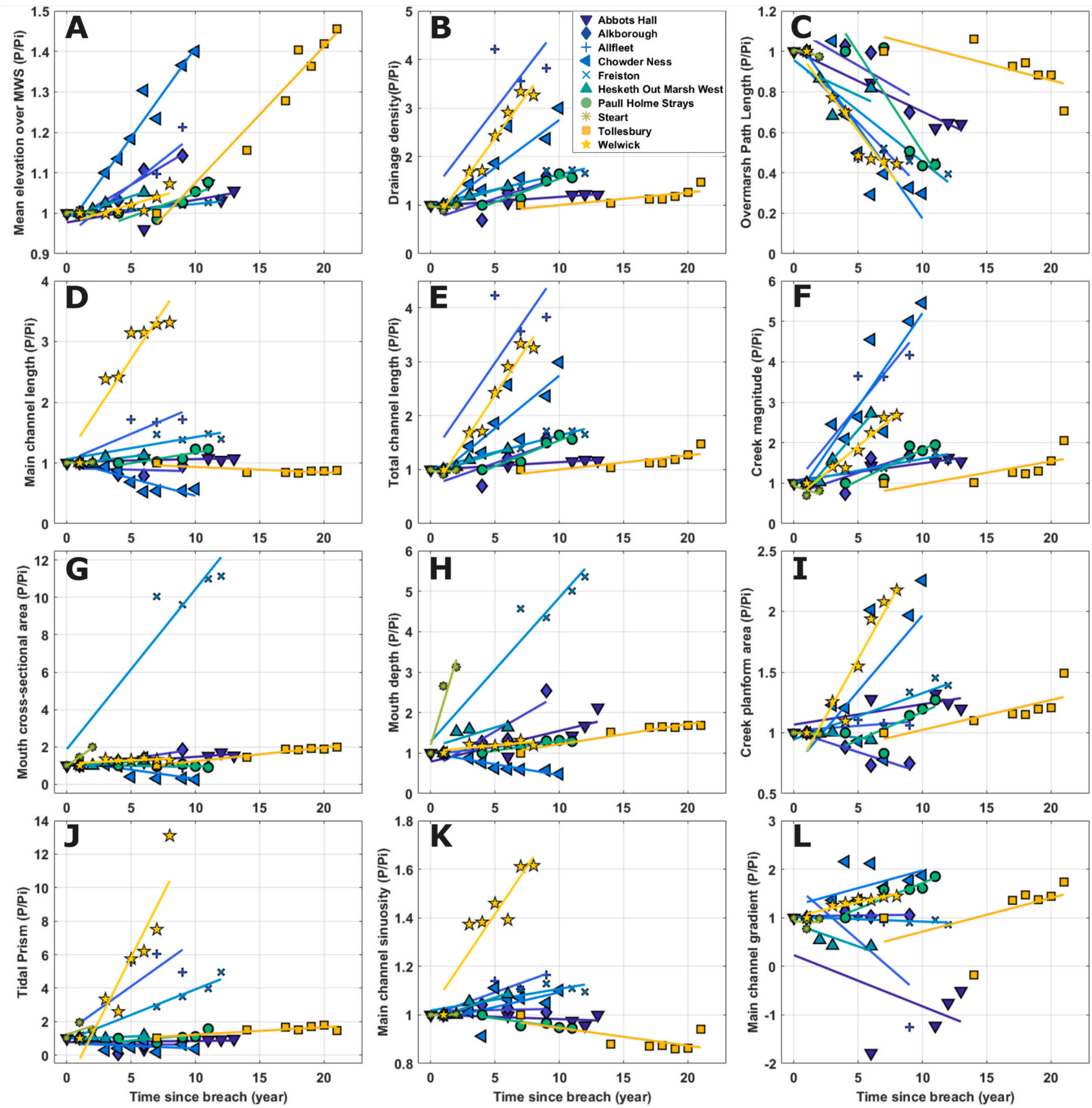

Fig. 3. Normalized evolution trends of MR mean elevation and creek parameters (P/Pi = Parameter/Initial parameter) since site implementation. Solid lines correspond to best linear fit. A: Mean elevation above MWS (%/yr); B: Drainage density (%/yr); C: Overmarsh path length (%/yr); D: Main channel length (%/yr); E: Total channel length (%/yr); F: Number of creeks (%/yr); G: Total mouth cross-sectional area (%/yr); H: Main channel mouth depth (%/yr); I: Planform area (%/yr); J: Undermarsh tidal prism (creek volume) (%/yr); K: Sinuosity ratio (%/yr); L: Main channel gradient (%/yr).

Table 3
Initial site conditions (groups 1–4), rates of elevation change and morphological creek evolution (group 5) considered in the PCA.

Parameters selected for PCA	Relevance to creek evolution
Means spring tidal range (m)	
Highest astronomical tide (m)	
Tidal asymmetry (ratio)	Tidal forcings (group 1)
Time embanked (years)	
Catchment area (m^2)	
Initial elevation above Mean Water Spring (m)	
Elevation gradient (ratio)	
Mean local slope (°)	
Topographical heterogeneity (m)	Initial MR morphology (group 2)
Largest initial outlet area (m^2)	
Largest initial outlet depth (m)	
Largest initial outlet width (m)	
Total initial outlet area (m^2)	
Total initial breach width (m)	
Initial tidal prism / Catchment area (m^3/m^2)	
Initial planform area / Catchment area (m^2/m^2)	
Initial total channel length / Catchment area (m/m^2)	
Initial overmarsh path length (m)	Initial breach and creek design (group 3)
Mean grain size in nearby estuary (μm)	
Turbidity in nearby estuary (ftu)	Sediment characteristics (group 4)
Mean elevation above mean spring level (%/yr)	
Drainage density (%/yr)	
Overmarsh path length (−%/yr)	
Main channel length (%/yr)	
Total channel length (%/yr)	
Number of creeks (%/yr)	
Mouth cross-sectional area (%/yr)	
Mouth depth (%/yr)	
Planform area (%/yr)	
Tidal prism (%/yr)	
Main channel sinuosity (%/yr)	Marsh elevation and creek morphological evolution rates (group 5)
Main channel gradient (%/yr)	

3.2. Links between creek evolution rates with the location and initial conditions of the MR sites

No trend is found linking the rate of creek evolution to the estuary they belong to: sites from the same estuary can exhibit contrasting evolution rates (see Alkborough, Chowder Ness and Welwick, Fig. 4). From site to site, the creek development is dominated by different morphometric parameters: we define a morphometric parameter as dominant when it contributes to over 50 % of the total creek development. Creek evolution at Chowder Ness and Hesketh Out Marsh West is dominated by the branching out of new creeks (increase in number of creeks and in total channel length); creek development at Steart and Welwick is dominated by an increase in creek volume (tidal prism); and creek development at Freiston is dominated by the widening and deepening of the entry channels (cross-sectional area). The fastest evolving MR creeks are those that are dominated by volumetric parameters, namely the breach cross-sectional area and the creek volume. This is because erosive processes near the breach occur earlier than the deposition-driven processes of creek expansion due to the higher hydrodynamic energy at the breach area, making that portion of the site highly dynamic. For example, at Freiston, the breach area has increased by ~10 m^2/yr over 12 years after implementation, and at Steart, the breach cross-sectional area has increased by ~71 m^2/yr over 2 years (Table 3).

More information on the factors driving creek evolution can be inferred from the PCA results. The first 4 Principal Components (PCs) cumulatively account for over 75 % of the total variability of the dataset (Table 4). The percentages of variability on the permuted, non-correlated datasets were on average 69 % for the first four PCs, with a standard deviation of 2.4 %. The one sample *t*-test found the variability explained by the first four PCs in the original dataset to be significantly greater than in the non-correlated datasets (t statistic = 2.67, critical cutoff value = 1.65, *p*-value <0.01). We conclude that the principal components represent real axes of variation rather than random directions.

Results from the PCA are displayed in a three-dimensional biplot to allow visual interpretation of the relationships between the variables (Fig. 5). Due to missing parameters relevant to saltmarsh development (e.g., vegetation, flow velocity, number of flooding events per year), PCs are not interpreted beyond the fourth component. Input variables were separated into the 4 PCs based on their highest absolute loadings (Table 5).

Most of the variables from group 5 (creek planimetric morphological evolution rates) are highly correlated with one another and with the first PC, which describes 28.58 % of the variability within the dataset (Table 5). PC 1 is also correlated with the total outlet area, representing either one large opening (Chowder Ness) or several breaches (Allfleet, Welwick). The variability at Welwick, where we observe a cluster of new creeks forming near the two large breach areas in the fronting saltmarsh (Fig. 5), is almost entirely described by PC1.

PC2 describes 23.87 % of the variability in the dataset and relates the initial MR creek template (PA and OPL) to the topographical heterogeneity, catchment area, outlet width and tidal forcings (MSTR, HAT and tidal asymmetry). This PC contrasts sites that lie at the elevation range of a middle-upper saltmarsh, have a small outlet and a high initial overmarsh path length (Alkborough), with sites that lie at the elevation range of a mudflat and have a comparatively larger outlet and more extensive initial creek system (Abbots Hall and Tollesbury).

PC3 (13.16 % of the variability) is positively correlated to the estimated mean grain size of the sites, to the elevation gradient, and to creek volumetric evolution rates (CSA, D, TP): Welwick and Freiston, which are characterized by erosional processes where the creek volume increases through the cutting of new creeks into the marsh and the deepening of existing creeks, have positive values along this principal component (See Appendix 4). PC3 is negatively correlated to the turbidity, accretion rates (MWS), initial breach area and the branching out of new creeks (NB): at Chowder Ness and to a lesser extent at Hesketh Out Marsh West, a high accretion rate due to a high sediment availability in the nearby estuary and a large outlet encourage the initiation of new creeks via differential deposition. PC3 therefore contrasts accretion-driven sites (Chowder Ness, HOMW) to erosion-driven sites (Welwick, Freiston).

PC4 (11.12 % of the variability) inversely relates the number of years that the site spent cut off from tidal influence prior to breaching (time embanked), to the elevation above MWS, initial largest outlet area, initial creek volume and mean channel gradient (MCG). MR sites that were embanked earlier historically tend to lie lower within the present-day tidal frame. The lower elevations are due to a combination of factors such as lower sea level at the time of reclamation (and hence lower height of saltmarsh surfaces), lack of ongoing sediment inputs, and compaction and drying during the embanked phase. Higher-lying sites tend to be designed with a higher initial creek volume and to have a higher elevation differential with the fronting intertidal areas, which explains the faster evolution of MCG.

3.3. Comparison with the equilibrium state of mature natural saltmarshes

Total channel length equilibrium, as defined by the power-law relationships established for the 13 mature natural saltmarshes, is reached at most MR sites within the monitoring period, with the exception of Alkborough (Fig. 6A). At Alkborough, the requirement to armour the breach to prevent expansion and limit the tidal exchange, and thus impacts on the wider estuary, appears to have limited the creek development within the site. However, for most sites, the cross-sectional area

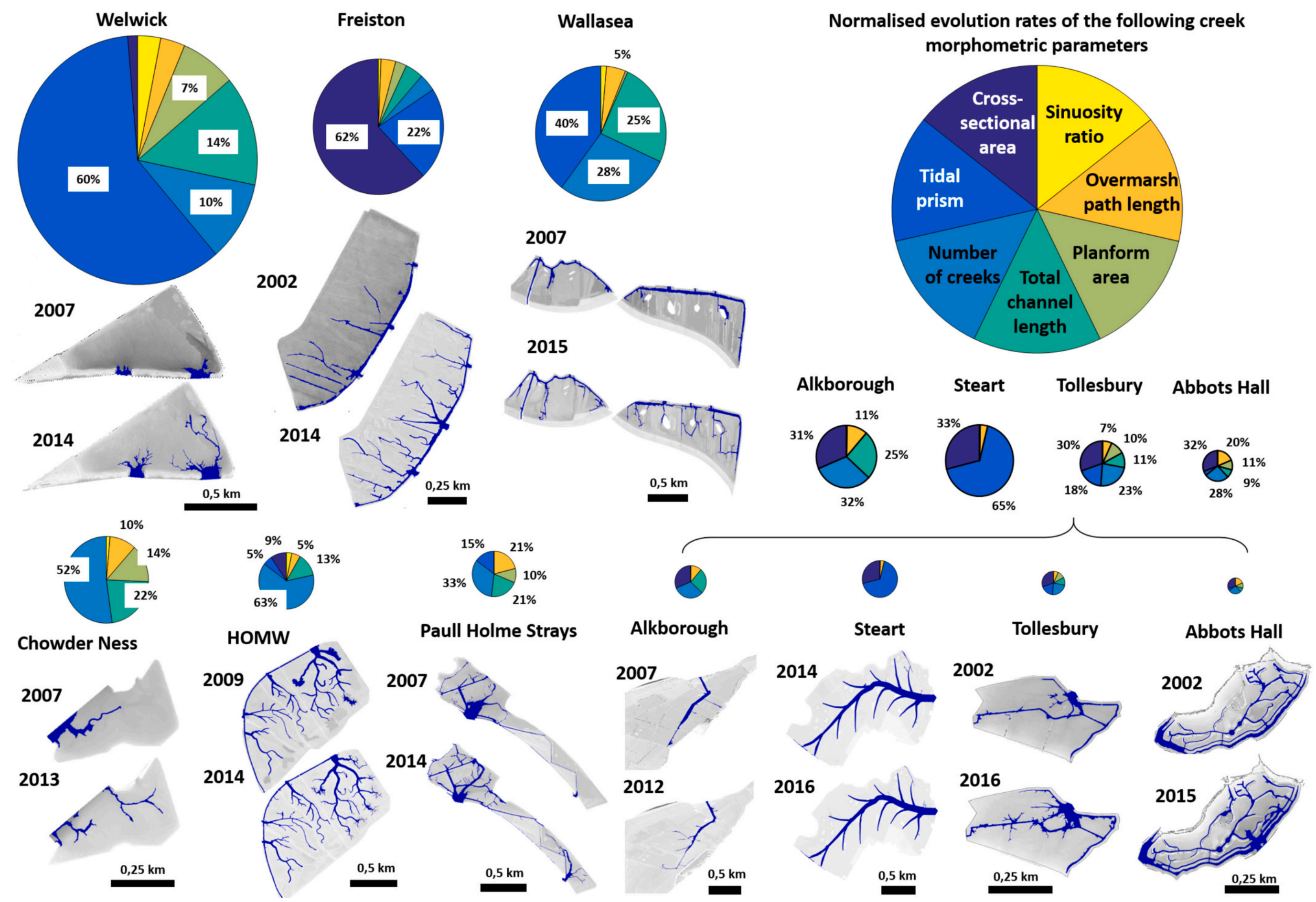

Fig. 4. Creek network morphometric evolution per MR site, ranked by total normalized evolution rates (creek extent for the first and last year of monitoring shown in blue). The size of the pie chart is proportional to the sum of the evolution rates for all considered parameters and indicates the most rapidly developing creek networks. Percentages show the contributions of each considered parameter to the overall evolution of the creek system (percentage contributions below 5 % are not shown).

compared to the tidal prism is above the equilibrium range (Allfleet, Freiston, Hesketh Out Marsh West, Paull Holme Strays, Tollesbury, Welwick) (Fig. 6B): breach cross-sectional areas tend to be larger than natural counterparts. Crucially, the overmarsh path length is above the equilibrium range for all MR sites, meaning that the spatial creek distribution is poor compared to natural mature saltmarshes (Fig. 6C). These results suggest that most of the creek length and volume is concentrated around the outlet, while the marsh interior remains empty of creeks (see Tollesbury and Welwick, Fig. 4).

The mean distance between creeks obtained via creek excavation during the implementation phase varies from site to site: 30 m for Abbots Hall, 50 m for Hesketh Out Marsh, Paull Holme Strays, Freiston and Tollesbury, 100 m for Chowder Ness and Allfleet, and over 100 m for Alkborough and Welwick. The overmarsh path length at Chowder Ness decreases from 100 m to 30 m over the 9 year monitoring period, due to the branching out of new creeks driven by spatial patterns in deposition. The overmarsh path length at Paull Holme Strays decreases from 50 m to 30 m over the 7 year monitoring period due to the branching out of new creeks: in this site, creek development seems caused by both depositional and erosional processes.

The ratio of planform area to catchment area of the creek system is similar for both natural and MR sites, even within 2 years of breaching (Fig. 7A). The ratio of creek volume to catchment area, however, starts initially lower in the MR sites than in the natural sites, but increases to become statistically similar natural sites after around 5 years (Fig. 7B). Indicators of creek network complexity (drainage density) and spatial distribution within the marsh (overmarsh path length) evolve towards those of natural mature systems, but MR creeks remain sparser and poorly distributed after 5–20 years compared to their natural counterparts (Fig. 7C-D). For 50 % of the dataset, overmarsh path length values range from 5 to 15 m in natural saltmarshes, from 65 to 225 m in the early stage of MR evolution, and from 33 to 101 m in the later stage of MR evolution, with median OPL values of 7 m, 110 m and 44 m respectively. The topographical heterogeneity is also lower in MR sites compared to natural mature saltmarshes (Fig. 7E).

Creek systems in MR sites start out with a lower branching complexity than in natural mature systems (maximum creek order 2–4 versus 3–5), and have a lower sinuosity and wider channels at all orders. Over >5 years of evolution, the branching complexity increases to match that of natural systems in the later stage and the sinuosity increases for most creek orders. The junction angles decrease and the number of low order creeks increases in the later stage because of the formation of clusters of creeks near the breaches. The detailed morphometric comparison between the creek systems in early-stage MR sites, later-stage MR sites and mature natural saltmarshes is provided in Appendix 5.

Table 4
Absolute evolution rates for MR elevation and creek morphological parameters given by the best linear fit (relative evolution rates in %/yr in parentheses). Significant correlations at a 0.05 significance level are shown in bold. Linear trends greater than the 95 % spread of the residuals are highlighted in light blue, 68 % in beige, 50 % in yellow. Trends inferior to the mean of the residuals are highlighted in red.

	Abbots Hall	Alkborough	Allfleet	Chowder Ness	Freiston	Hesketh Out Marsh West	Paull Holme Strays	Steart	Tollesbury	Welwick
Mean elevation over MWS in cm/yr (%/yr)	0.78 (0.56)	**4.43 (1.90)**	2.42 (2.51)	**10.30 (4.42)**	0.76 (0.30)	**4.33 (1.03)**	**3.26 (1.14)**	-0.17 (-0.03)	**2.89 (3.36)**	**2.23 (0.92)**
Drainage density in km/km2/yr (%/yr)	**0.43 (1.89)**	0.07 (8.60)	0.90 (34.48)	**1.13 (19.67)**	**0.43 (6.16)**	**0.68 (7.76)**	**0.95 (9.65)**	--0.01 (0.29)	**0.31 (2.59)**	**0.80 (36.25)**
Overmarsh path length in -m/yr (-%/yr)	**0.80 (3.02)**	28.33 (3.66)	7.62 (6.55)	**9.12 (9.01)**	**5.54 (5.03)**	1.58 (2.96)	**5.59 (9.75)**	1.13 (1.33)	0.87 (1.64)	**21.88 (8.36)**
Main channel length in m/yr (%/yr)	2.41 (0.45)	-9.80 (-0.53)	33.64 (8.98)	**-15.70 (- 5.74)**	**14.81 (3.63)**	29.58 (2.64)	30.49 (3.49)	8.09 (0.32)	-5.88 (-0.89)	**75.11 (31.98)**
Total channel length in m/yr (%/yr)	**79.53 (1.40)**	247.00 (8.37)	880.16 (34.57)	**113.20 (19.56)**	**301.29 (6.18)**	**1069.51 (7.70)**	**758.98 (9.59)**	-15.84 (-0.17)	**59.33 (2.62)**	**434.63 (36.17)**
Number of creeks in yr^{-1} (%/yr)	**2.50 (4.31)**	3.26 (10.53)	18.79 (39.14)	**5.07 (46.11)**	**4.31 (5.83)**	**55.43 (36.71)**	**14.67 (15.28)**	-7.50 (-9.74)	2.74 (5.60)	**9.77 (26.40)**
Mouth cross-sectional area in m2/yr (%/yr)	**0.80 (4.96)**	**1.68 (10.31)**	-1.11 (-1.32)	-0.89 (-9.66)	**9.86 (85.60)**	6.59 (5.40)	-1.24 (-0.81)	**70.64 (49.30)**	**2.50 (7.32)**	3.30 (3.41)
Mouth depth in m/yr (%/yr)	0.03 (7.60)	0.17 (18.37)	**0.08 (3.61)**	**-0.08 (-5.41)**	**0.30 (35.57)**	0.21 (9.84)	0.09 (4.66)	2.31 (105.92)	**0.10 (4.95)**	**0.03 (2.95)**
Planform area in m2/yr (%/yr)	706 (1.68)	-2201 (-3.41)	570 (0.79)	729 (12.44)	**1639 (3.80)**	-2268 (-1.23)	3898 (4.64)	**-1244 (-0.49)**	**408 (2.46)**	**3366 (18.93)**
Tidal prism in m3/yr (%/yr)	144 (0.76)	-2 (-0.28)	4880 (54.67)	-93 (-3.10)	**3229 (30.41)**	3812 (3.16)	1967 (6.94)	29611 (25.04)	**138 (4.43)**	**702 (151.66)**
Main channel sinuosity in yr^{-1} (%/yr)	-<0.01- (0.19)	<0.01 (0.09)	0.03 (1.89)	0.01 (1.20)	0.01 (0.89)	0.02 (1.82)	**-0.01 (-0.72)**	<0.01 (0.11)	<0.01 (-0.73)	**0.09 (7.84)**
Main channel gradient in °/yr (%/yr)	-0.04 (-9.64)	<0.01 (0.31)	-0.30 (-22.96)	0.08 (7.23)	-0.03 (-0.98)	-0.20 (-9.31)	**0.06 (10.55)**	-0.05 (-0.88)	0.07 (6.93)	**0.11 (5.94)**

4. Discussion

4.1. Observed morphological differences between the creek networks of natural mature saltmarshes and MR sites

The aim of this paper is to quantify creek network evolution in MR sites relative to design choices, and assess how well they mimic natural systems, in order to optimise creek designs in future projects. Time-series of creek morphology show that the monitored MR creeks increased in total length, volume, structural complexity and extent with time. Creek volume increases rapidly in the first 5 years post-breach and becomes statistically similar to that of a mature natural system within this timeframe. However, even faster-growing creeks in MR sites retain a lower drainage density and greater overmarsh path length compared to their natural counterparts. Rates of morphological evolution vary between MR sites situated in the same estuary, suggesting that the on-site conditions play an important role on creek development compared with the estuarine context.

Creek network evolution is influenced by the initial morphology of the site — the initial creek template and previous drainage ditches remain clearly visible after 20 years of evolution (Fig. 2). The long-term legacy of inherited structures such as drainage ditches was also observed in similar projects in other countries such as Canada (MacDonald et al., 2010) and the Netherlands (Vandenbruwaene et al., 2012). These findings are in accordance with previous observations that saltmarsh creeks largely inherit the pattern formed in the preceding mudflat environment (Allen, 1995; Steel and Pye, 1997; Taramelli et al., 2018).

MR creek evolution is driven by the focusing of predominantly tidal energy through one or several large outlets i.e. the breaches. For MR sites, lengths of former flood embankment either side of breaches limits the exchange of tidal water over the most seaward edge of the marsh as happens in natural settings with no embankments. A large breach, in conjunction with high sediment availability in the estuary and a low initial elevation, encourages the formation of new creeks via deposition. However, low topographical heterogeneity reduces the creation of preferential flow paths, as highlighted by Lawrence et al. (2018). Erosional processes of marsh formation (headward erosion, formation of new creeks at the bend of channels) are encouraged by high tidal forcings, large outlets and the presence of an elevation gradient within the site and of topographical heterogeneity.

Erosion is also likely to be hindered by the high compaction of MR soils (Brooks et al., 2015; Spencer et al., 2017; Tempest et al., 2015). Indeed, while this study focuses on aboveground morphological properties, creek development also depends on belowground processes. Interactions between sediment, plant roots and macropores have an impact on the shear strength of saltmarsh sediment (Chirol et al., 2021). Saltmarsh plants can affect erosion rates within a marsh depending on their root traits (Bernik et al., 2021). Bioturbation and burrowing species also affect belowground water circulation and erosion patterns, and their diameter depend on the distance to the creek network, as seen for crab burrows (Xie et al., 2022).

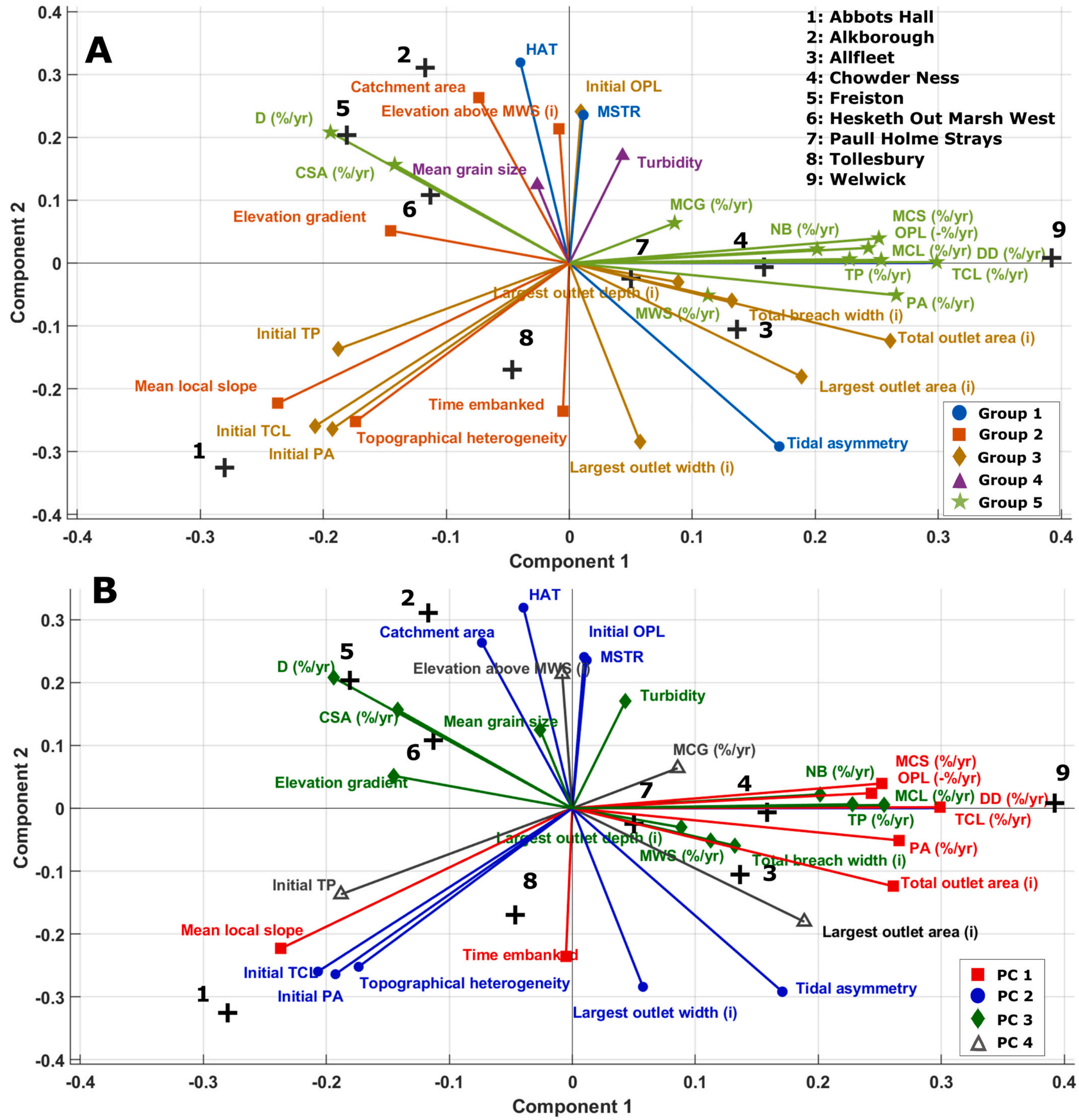

Fig. 5. Biplot of normalized variables for all MR sites, with the first two PCs as axes. The cosine of the angle between two vectors represents the correlation coefficient between these variables, and the cosine of the angle between a vector and a PC-axis measures the correlation between them. A: Distribution of the variables across the 5 variable groups detailed in Table 4 (Group 1: tidal forcings; group 2: initial MR morphology; group 3: initial breach and creek design; group 4: sediment characteristics; group 5: morphological evolution rates). B: Contributions of the variables to PC1 (red squares) and PC2 (blue dots). Contributions of variables to PC3 are shown as green diamonds and to PC4 as black empty triangles. Position of each MR site within the biplot shown as black crosses, following the numbering of Fig. 1. The dataset used to obtain the PCA is given in Appendix 3. Graphical representation of principal components 2 and 3 is given in Appendix 4.

4.2. Conceptual model of creek evolution in MR sites and expected consequences for MR functioning

We propose a new four-stage conceptual model of MR creek evolution as marsh elevation increases to an equilibrium with tidal range, focused on four key morphological variables (Fig. 8). The breach cross-sectional area typically increases rapidly and stabilises above the equilibrium range due to the flow being forced through the breach by the remaining embankments (Stage 2). Erosion leads to the deepening of the entry channel immediately upstream of the breach and to a rapid increase in creek volume, but the absence of sufficient flow routing further landwards leads to premature energy dissipation in a cluster of smaller creeks near the breach (Stage 3). In stage 3, the number of creeks increases in the lower regions near the breach, but also in headward

Table 5
Loadings for the first 4 principal components (PC), explaining over 75 % of the total variation, following PCA applied on standardized variables for all MR sites. Groups of correlated variables are shown in red for PC1, blue for PC2, green for PC3 and black for PC4.

Variable groups	Variables	PC1	PC2	PC3	PC4
Group 1: Tidal forcings	MSTR	0.011	**0.235**	-0.055	-0.304
	HAT	-0.040	**0.319**	-0.102	-0.186
	Tidal asymmetry	0.171	**-0.292**	0.064	-0.070
Group 2: Initial MR morphology	Time embanked	-0.005	-0.236	-0.058	**0.364**
	Catchment area	-0.073	**0.263**	-0.115	0.221
	Elevation above MWS (initial)	-0.008	0.214	-0.022	**-0.324**
	Elevation gradient	-0.145	0.051	**0.317**	-0.040
	Mean local slope	**-0.237**	-0.223	-0.019	0.045
	Topographical heterogeneity	-0.174	**-0.252**	0.094	0.128
Group 3: Initial breach and creek design	Largest outlet area (initial)	0.189	-0.181	-0.013	**-0.206**
	Largest outlet depth (initial)	0.088	-0.030	**-0.211**	-0.037
	Largest outlet width (initial)	0.057	**-0.284**	0.048	-0.203
	Total outlet area (initial)	**0.261**	-0.124	0.101	-0.082
	Total breach width (initial)	0.132	-0.060	**-0.205**	-0.130
	Initial TP	-0.188	-0.137	-0.089	**-0.230**
	Initial PA	-0.193	**-0.264**	0.012	-0.105
	Initial TCL	-0.207	**-0.260**	0.035	-0.171
	Initial OPL	0.010	**0.241**	-0.069	0.254
Group 4: Sediment characteristics	Turbidity	0.043	0.171	**-0.302**	-0.006
	Mean grain size	-0.026	0.124	**0.371**	-0.116
Group 5: Marsh elevation and creek morphological evolution rates	Mean elevation over MWS (%/yr) -MWS	0.113	-0.051	**-0.325**	0.055
	Drainage density (%/yr) -DD	**0.298**	<0.001	0.048	0.191
	Overmarsh path length (-%/yr) -OPL	**0.243**	0.024	-0.003	-0.154
	Main channel length (%/yr) -MCL	0.228	0.006	**0.274**	0.071
	Total channel length (%/yr) -TCL	**0.299**	0.002	0.048	0.190
	Number of creeks (%/yr) -NB	0.202	0.022	**-0.205**	-0.009
	Mouth cross-sectional area (%/yr) -CSA	-0.142	0.156	**0.308**	-0.032
	Mouth depth (%/yr) -D	-0.194	0.208	**0.253**	0.052
	Planform area (%/yr) -PA	**0.266**	-0.051	0.130	-0.195
	Tidal prism (%/yr) -TP	0.254	0.005	**0.268**	0.094
	Main channel sinuosity (%/yr) -MCS	**0.252**	0.039	0.194	0.025
	Main channel gradient (%/yr) -MCG	0.086	0.064	-0.017	**-0.355**
Explained variability (%)		**29**	**24**	**13**	**11**
Cumulative explained variability		**29**	**52**	**67**	**77**

ponds (if present in the design) where accretion rates are high. Existing drainage ditches and borrow dikes can also contribute to the extension of the creek network at this stage through incorporation (if the channels are present but not connected) and/or re-erosion (if the channels have been infilled). The creek distribution remains below the natural equilibrium range because the creek system cannot expand significantly beyond its initial template due to the high position within the tidal frame, the relatively low tidal energy in the marsh interior, and potentially the effect of soil compaction. Creeks inherited from drainage ditches remain overly straight and show no sign of expansion or branching. Based on Steel and Pye's (1997) model, the final stage should see the creek network stabilise or shrink and the creek volume diminish as the number of tidal events reaching the site becomes lower (expected Stage 4), however the managed realignment sites considered in this study are not old enough for us to observe this behaviour.

The observed differences in creek morphology between MR and natural saltmarshes may negatively affect marsh functioning. Less extensive (lower drainage density) and less effective (higher overmarsh path length) creek networks have been linked to a lower exchange of water, sediment and nutrients between the marsh surface and the adjacent estuary compared to a natural system (Schwarz et al., 2022). These exchanges are also probably less well distributed in MR sites compared to natural saltmarshes since the majority of the spontaneously incised creeks form near the breach area. Saltmarshes with less efficient creek networks might perform poorly at mitigating vegetation degradation by droughts (Liu et al., 2020). Poorly developed creek systems may be one factor in explaining why MR sites have been observed to not provide the same ecosystem services as their natural counterparts (Brady and Boda, 2017; Esteves, 2013), and in particular do not replicate the full plant diversity of natural wetlands (Mossman et al., 2012). Studies comparing MR creek morphological characteristics to indices of ecosystem function are needed to better incorporate this

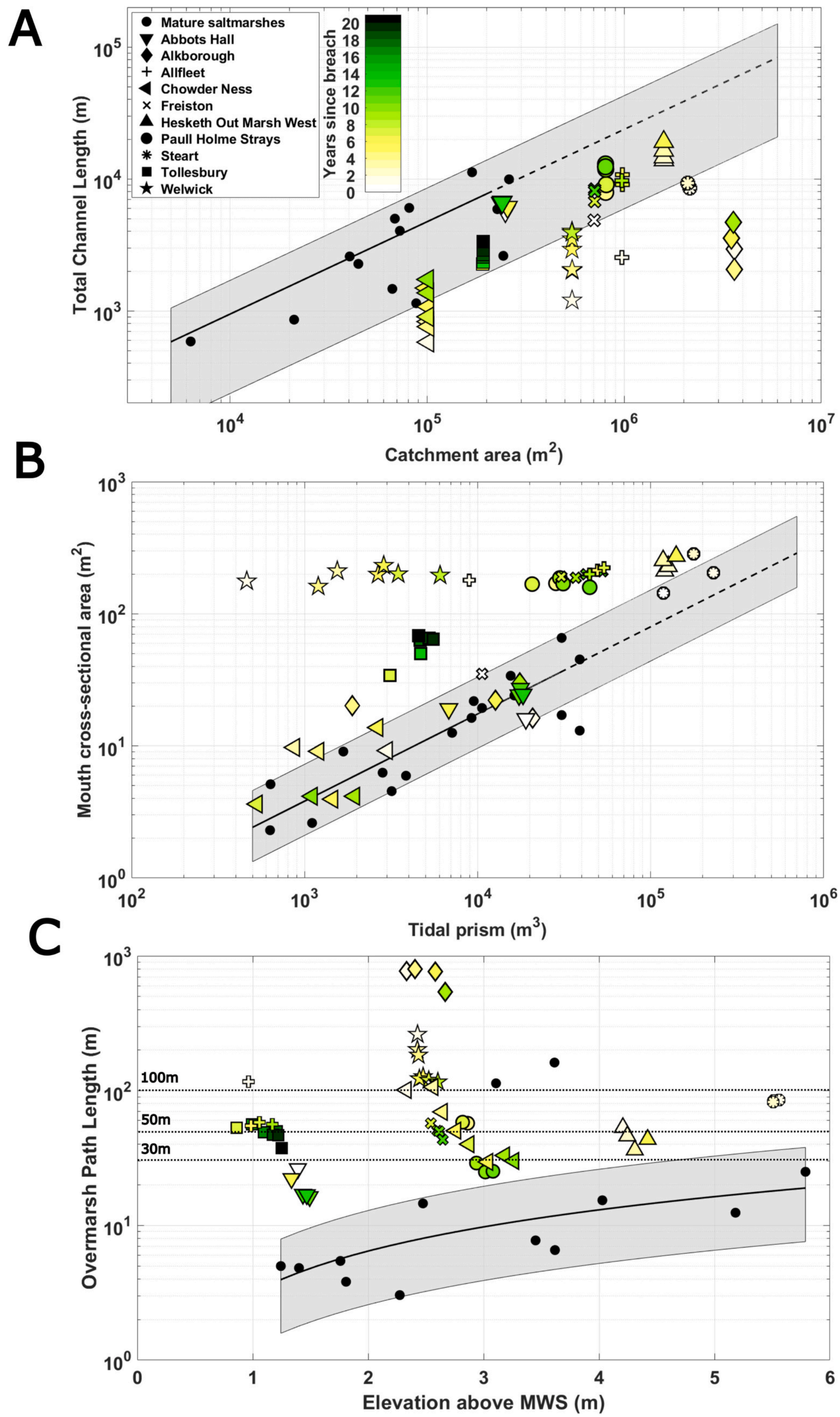

Fig. 6. MR creek evolution relative to the morphological equilibrium range established for 13 natural mature saltmarshes (grey band). The solid black line represents the equilibrium state as interpolated from the 13 mature saltmarshes, and the dashed black line represents the extrapolation of that equilibrium state. A: Total channel length versus catchment area. B: Mouth cross-sectional area versus tidal prism. C: Overmarsh path length versus elevation above mean water spring (MWS). Dotted lines show a mean distance between creeks of 100, 50 and 30 m.

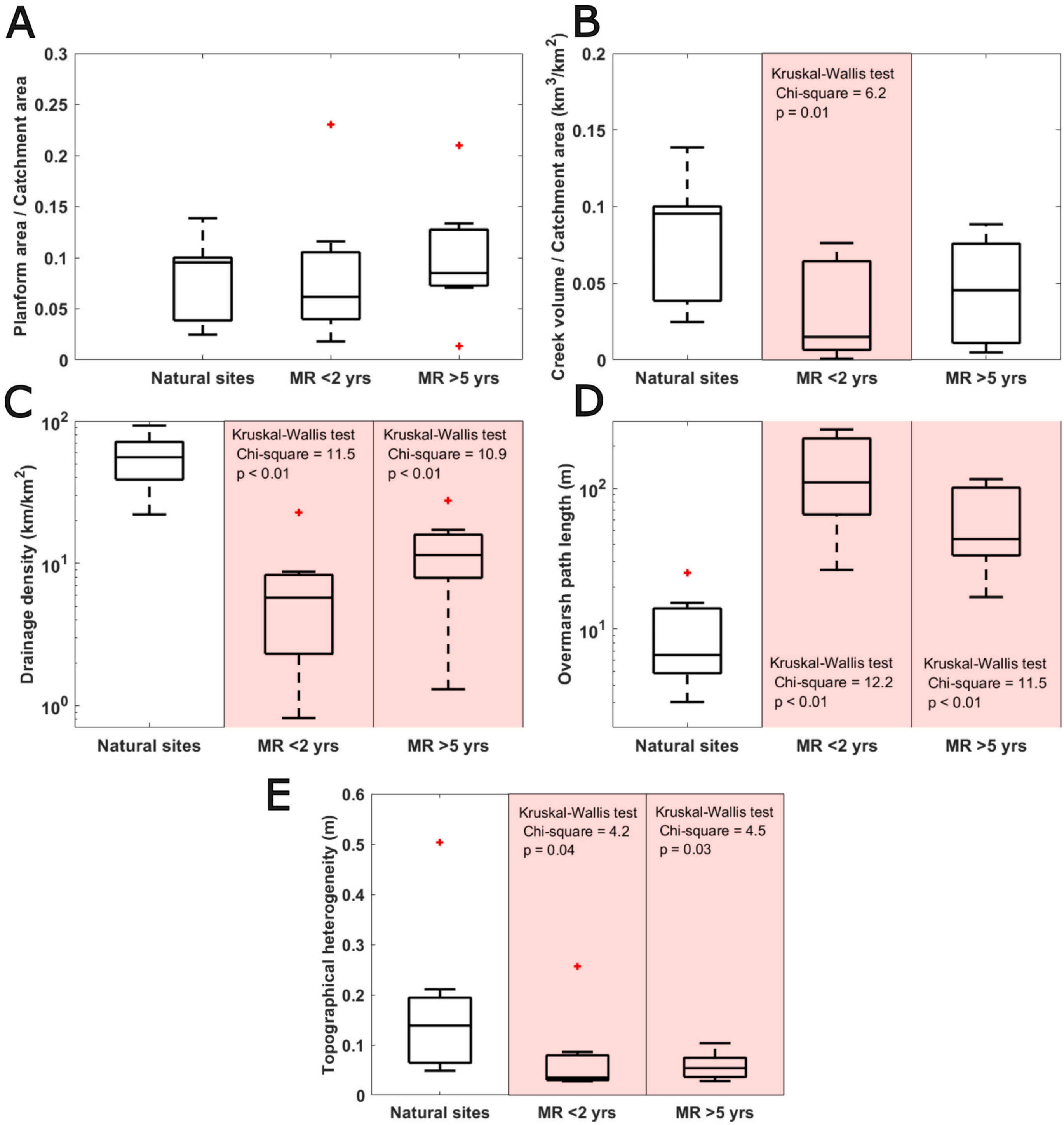

Fig. 7. Kruskal-Wallis comparison of creek morphological parameters and topographical heterogeneity between natural mature saltmarshes, MR sites after <2 years of evolution post-breach, and MR sites after >5 years of evolution. Red shading represents a significant difference from the natural mature saltmarshes according to Kruskal-Wallis at a 95 % confidence interval. A: Planform area / catchment area. B: Creek volume / catchment area. C: Drainage density. D: Overmarsh path length. E: Topographical heterogeneity.

interdependence between structure and function in future saltmarsh restoration strategies (Crotty and Angelini, 2020).

4.3. *Implications for the design of creeks in restored marshes*

Best practice for restoration projects is to try and replicate the conditions found within natural sites as far as is possible. This is especially important for sites that are delivering compensatory habitat. A number of previous authors (Pontee, 2003; Larson et al., 2018; Adam, 2019) have observed that creating the correct physical conditions, including creek morphology, is necessary to achieve the correct habitats.

Comparing restored marshes to natural marshes in the UK shows several differences in creek shape and repartition. The branching complexity is the same but tends to be concentrated over a small area of the MR site, around the breach areas where the elevation is lower and the connection to the wider estuary increases the hydrodynamic forces.

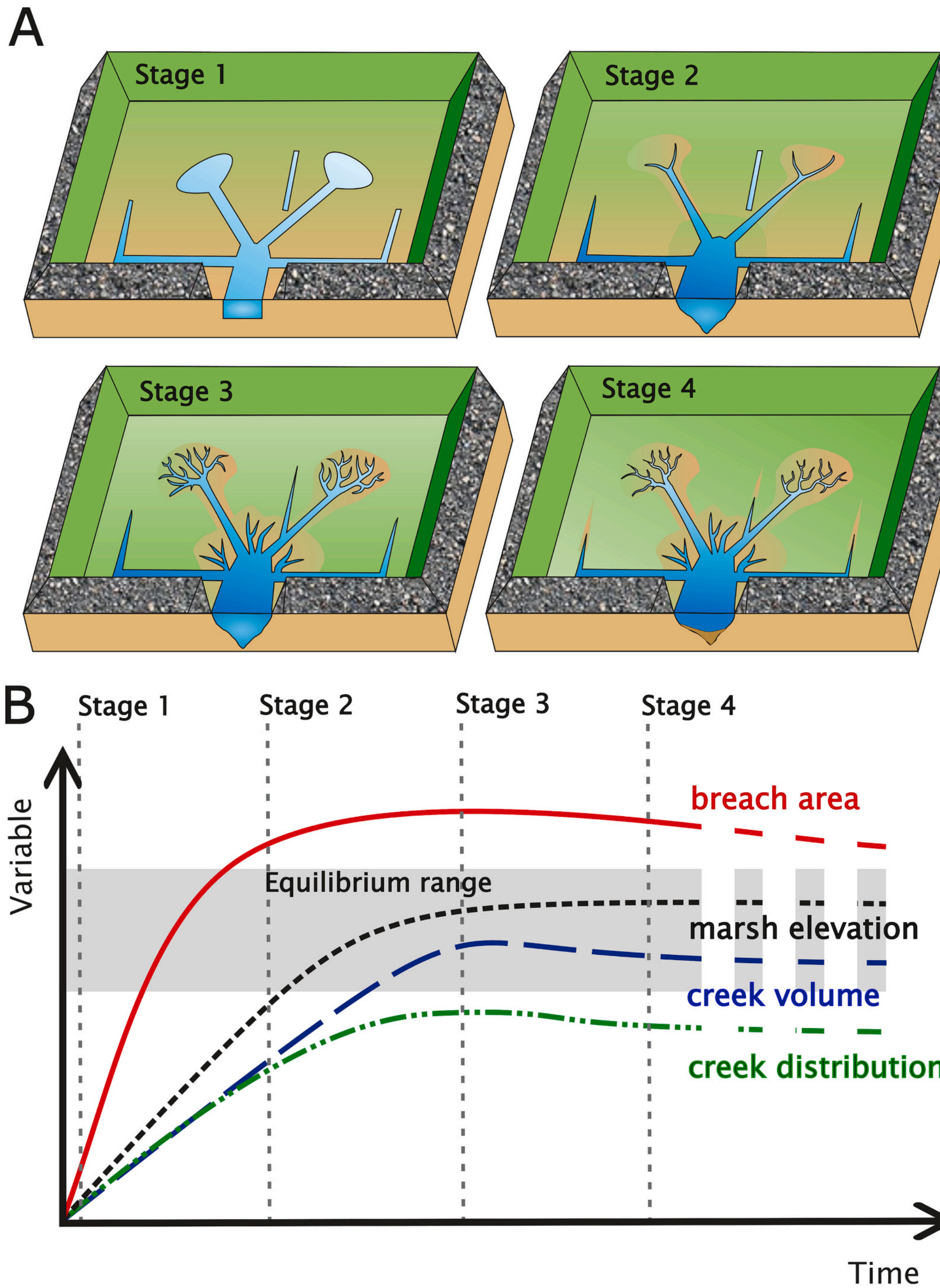

Fig. 8. A: Conceptual morphological evolution model of MR creek networks based on the synthesis of our observations at 10 MR projects in the UK. B: Evolution of key variables as marsh elevation increases to equilibrium with the tidal range. The broken lines at the end of the graph represents the extrapolation of the observed trend and a hypothesis of how the system may stabilise in stage 4. The conceptual model attempts to capture general trends and is not going to apply to every individual site.

This is expressed by a similar number of orders but an over-representation of low Reverse Strahler order (i.e. large) creeks, a lower junction angle for the second order creeks, and greater overmarsh path lengths. Natural marshes have a mean distance between creeks (33 m to 101 m) that is (a) much larger than restored marshes (5 to 15 m); and (b) larger than common guidance for the maximum distance between creeks (<30 m). Restored marshes in the UK should ideally aim for values with the range of 5 to 15 m based on what we observe in natural mature saltmarshes. Among the sites considered, Abbots Hall, Paull Holme Strays and Chowder Ness achieve some of the smallest creek separation distances: this can be attributed to the low-lying nature of the sites in addition to high sediment supply which allow creeks to form within freshly deposited sediment.

We suggest that creeks are most likely to form naturally in MR sites that (1) have extensive areas of land lying below MHW which allow space for sedimentation; (2) are located in estuaries with high suspended sediment concentrations, which ensures high supply for sediment for accretion within the site; (3) are not overly compacted in the higher areas of the site (above MHWN) so that the formation and deepening of new creeks by erosion processes is possible; and (4) have high flow speeds to facilitate sediment erosion. Conversely, creeks are less likely to form in sites where none of these conditions are met.

Where creeks are less likely to form unassisted and develop towards equilibrium in MR sites, more extensive engineering works are be required to create conditions comparable to reference sites. We recommend that creek design in MR sites be preceded by the following measurements to assess how much engineering work will be needed: (1) in situ shear strength measurements for the erosion resistance of sediments within the site; (2) hydrodynamic modelling to determine likely flow speeds within the sites, and (3) an assessment of siltation rates on nearby marshes at a similar range of elevations to derive likely siltation rates. These data could be incorporated in spatially explicit creek formation models to verify whether conditions for channel extension are met for a given design of site elevation and creek morphology. Models have been developed for sedimentation-driven (Fagherazzi et al., 2012) and erosion-driven creek development (D'Alpaos et al., 2007). Recent studies using such models have found that the creek network design affects both biogeomorphic development and the resilience of the restored marsh to rising sea levels (Gourgue et al., 2022).

We note that despite best intentions for restored sites to have creek systems that accurately mimic reference sites, final creek designs may differ from idealised relationships in natural marshes for a number of practical engineering reasons. The need to minimise financial and carbon costs of construction may limit the amount of excavation that is undertaken. Moreover, the need to limit the import/export of construction material from the site creates constraints in the amount of excavation undertaken to balance the cut (e.g. excavation of creeks) and fill (e.g. embankment construction) requirements. There are also practical difficulties in excavating very small and complex channels which may preclude their construction. Other requirements may also affect the layout of the excavated creek system including the avoidance of areas of archaeological interest or the need to keep the site easily accessible for grazing. Another constraint on the constructed creek layout is the number and location of breaches, which is determined by several factors including the impacts on flood risk in the wider estuary (Pontee, 2015b), the risk of eroding existing habitats, and the requirements to maintain footpath access (e.g. by bridges). Ultimately final design for creek systems, as for the wider schemes, represents a balance of multiple aspects.

We also highlight that these points of guidance are targeted towards obtaining a rapidly developing creek network that evolves into a morphology close to that of natural systems, based on the widely-held assumption that this will improve marsh functioning. However, the notion of a "successful" saltmarsh restoration project is subjective and depends on the priorities surrounding a given project, especially since trade-offs can occur between saltmarsh functions (e.g. its capacity to provide biodiversity and its capacity for flood mitigation (Schuerch et al., 2022)). Still, power-law relationships as descriptors of an end-goal morphological equilibrium state can help to set quantifiable targets for MR sites, especially where no nearby natural marsh can be used as reference, and provide an economical alternative to process-based numerical modelling for creek network design in MR sites (Hood, 2020).

5. Conclusions

The overall aim of this study was to quantify how the morphology of MR creek networks evolves and differs from the equilibrium state of natural systems to provide guidance for future projects, using 10 MR sites from the UK as case studies. Over 5 to 20 years of monitoring, we observe a near-linear evolution of creek morphological parameters (total channel length, drainage density, mean distance between creeks), and that the creek volume and order complexity become comparable to that of natural systems. However, creek development occurs mainly in a cluster of low junction angle creeks around the breach areas, while the marsh interior remains empty of creeks, especially in sites that start above Mean High Water. Initial template and signs of the previous agricultural use such as drainage ditches remain clearly visible. The common recommendation that creek systems must be implemented with a 30 m distance between creeks is fulfilled for only 3 out of the 10 MR sites considered, and most sites range between 33 and 101 m, versus 5 to 15 m for natural mature saltmarshes. The lower drainage efficiency at MR sites, associated with lower topographical heterogeneity and consolidated substrates, are suspected to negatively impact marsh functioning.

We proposed a new conceptual model to represent creek design and evolution in current MR sites in the UK. Creek development in MR sites occurs dominantly in a cluster of creeks with low junction angles around the breach areas, where most of the hydrodynamic energy is concentrated. Creek expansion is hindered by the lack of topographical heterogeneity which typically promotes spatial patterns of deposition. Headward erosion is hindered by the consolidated soil typically found in MR sites. For all these reasons, the creek network shape in the marsh interior is constrained by the initial design of the site, especially by the overly straight channels inherited from drainage ditches.

Ultimately the goal of restoration is to achieve the replication of reference site conditions within the restored sites. We have developed a conceptual framework for identifying where creeks are more/less likely to form unassisted within realignments sites and thus where less/more engineering effort is required to help achieve reference site conditions. We note that the final design of creeks will also require the consideration of various other practical factors that will vary between sites.

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CRediT authorship contribution statement

C. Chirol: Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **N. Pontee:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **S.L. Gallop:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **C.E.L. Thompson:** Writing – review & editing, Supervision. **H. Kassem:** Writing – review & editing. **I. D. Haigh:** Writing – review & editing, Supervision, Software, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

The data interpreted and discussed in this paper has been made available in a Data Paper, which is cited in the textha

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Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171067.

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