

1 **Coastal saltmarsh managed realignment drives rapid**
2 **breach inlet and external creek evolution, Freiston Shore**
3 **(UK)**

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17 **Abstract**

18 The creation of saltmarsh through the managed realignment of sea defences, implemented in northwest
19 Europe as a sustainable coastal defence option, represents a substantial hydrodynamic perturbation to
20 the local coastal system. The impact of a significantly increased tidal prism on hydromorphological
21 features was investigated at Freiston Shore, Lincolnshire UK. Local tidal conditions and inadequate
22 drainage at this realignment trial contributed to significant channel erosion due to the establishment of
23 water surface slopes and pooling between the newly realigned site and the site-external intertidal zone.
24 Very high spatial resolution aerial and blimp photography was used to monitor inlet evolution from
25 breaching in August 2002 to March 2008, showing a highly non-linear response with breach channels
26 increasing in width by up to 960% within 2.5 months. Airborne Laser Scanning/LiDAR and Terrestrial
27 Laser Scanning quantified breach channel volume increases, showing a similar pattern. Breach
28 channel evolution did not follow established tidal prism-channel width/cross-sectional area
29 relationships that are often used to guide realignment design. Pre- and post-breach rates of external
30 creek morphology change between 1999 and 2006 were also quantified, with intertidal creeks attached
31 to the breach channels increasing significantly after realignment in both width and depth. This study
32 highlights the physical processes affected by managed realignment, and the importance of
33 understanding the causes of complex water surface slopes at multiple scales.

34

35 **Keywords:** erosion, geomorphology, hydromorphology, LiDAR, Terrestrial Laser Scanning, wetland

36

37 **1. Introduction**

38 Continuing loss and degradation of wetlands on low-lying mid-latitude coasts, and the appreciation of
39 the ecosystem services provided by saltmarshes (Zedler and Kercher 2005) has led to the use of
40 coastal management options that attempt to re-create saltmarsh on formerly reclaimed agricultural land.
41 The ‘managed realignment’ of coastal defences by breaching the former sea defence line to create a
42 new intertidal surface for saltmarsh development has been increasingly implemented in North-west
43 Europe (Rupp-Armstrong and Nicholls 2007) and North America (e.g. Williams and Orr 2002), with

44 150 realignment trials identified since the early 1990s (Spencer and Harvey 2012). However, on a
45 process level, managed realignment represents a sudden, significant hydrodynamic perturbation to the
46 equilibrium that may exist between flood and ebb tidal discharge and channel dimensions. Such a
47 sudden increase in the local tidal prism may have profound consequences for tidal circulation and
48 intertidal zone erosion and deposition in general, and tidal flow and sediment transport patterns
49 through inlet systems (sea defence breaches, existing intertidal creek networks) in particular.

50

51 The tidal prism is one of the main factors controlling tidal channel geometry (Vandenbruwaene et al.
52 2012a), such that an equilibrium channel form may be expected for a particular marsh tidal prism
53 within a defined tidal range (O'Brien 1931, 1969, Williams et al. 2002). This geomorphological
54 relationship can be used to assess inlet stability and to categorise inlets as erosional or depositional
55 (Mirfenderesk and Tomlinson 2008). Optimal breach channel design should create a stable inlet for
56 water exchange, with minimum scouring and jetting (Townend 2008). Breach dynamics are also
57 important in the context of hydraulic efficiency of the wider intertidal zone. During the ebb tide, water
58 stored at higher elevation within the hydraulically inefficient marsh surface *vs.* water removed within
59 the lower elevation, hydraulically-efficient creek channels (of which breaches are a part) sets up a
60 water surface slope, with an associated increase in flow velocities (Bayliss-Smith et al. 1979, Healey
61 et al. 1981, French and Stoddart 1992), or 'channel-forming flows' (Williams et al. 2002). In some
62 cases, the impacts of water surface slopes may extend well beyond the breach itself, impacting natural
63 saltmarsh drainage systems seaward of the managed realignment area.

64

65 It is important to accurately quantify the volume of water exchange through breach inlets, as they
66 control erosional processes at points of water exchange (breach channels) and water transfer (creeks),
67 and sediment depositional processes close to these features. However, while single breach channel
68 design may take into account the basic principles of hydraulic geometry, the detailed flow patterns that
69 may result from breaching are, at best, difficult to predict if site geomorphology is complex, and/or a
70 series of breaches, rather than a single breach, connects a managed realignment site to the existing
71 intertidal zone. The configuration of feeder creeks outside, and engineered channels inside the

72 realignment site, may lead to more complex flow patterns than simple periodic flood – ebb tide
73 reversals, and unexpected (and potentially non-linear) morphological responses both of the breach
74 channel themselves, and the tidal creeks that connect to them at more seaward locations.

75

76 This study fills an important knowledge gap regarding physical processes and disturbance in realigned
77 marshes (Spencer and Harvey 2012) by investigating the short- (0-1 years) and medium-term (1-5.5
78 years) hydromorphological evolution of channels at a managed realignment site at Freiston Shore,
79 eastern England. In particular, this study compares observed change in the sea wall breaches and
80 intertidal creeks with established hydromorphological equations for optimal inlet design (O'Brien
81 1931, CIRIA 2004). Freiston Shore provided a rare experimental opportunity to quantify the impacts
82 of a large hydrodynamic perturbation on water exchange and creek dynamics, and can provide
83 important guidance for future saltmarsh creation.

84

85 **2. Regional setting**

86 Freiston Shore is situated in The Wash embayment, eastern UK (Figure 1a). The Wash experiences a
87 macrotidal regime (Mean Spring Tidal Range (MSTR) = approximately 6.5 m), and covers an area of
88 615 km² below the high water level, with a mean spring tidal prism of 2.8 x 10⁹ m³ (Ke et al. 1996).
89 Mean High Water Spring (MHWS) equates to 3.3 m Ordnance Datum Newlyn (m ODN, where 0.0 m
90 ODN approximates Mean Sea Level (MSL)), while Mean Low Water Spring (MLWS) equates to -3.0
91 m ODN. Mean wave heights of 1.2 - 1.4 m are experienced during southwesterly gales (mean wind
92 speeds: 13.9 – 24.4 m s⁻¹) between November and March (Ke et al. 1996). The Wash is sediment-rich,
93 with nearshore suspended sediment concentrations in the range of 200 mg l⁻¹, and reaching an order of
94 magnitude higher during some events (Collins et al. 1981).

95

96 [FIGURE 1 HERE]

97

98 An extensive shallow-sloping intertidal zone fronts Freiston Shore (Figure 1b, 1c, Figure 2, Figure 3).
99 The main depositional environments are well described, comprising three different sandbank
100 environments and a lower mudflat below 1.5 m ODN, an algal-dominated upper mudflat up to 2.4 m
101 ODN, and saltmarsh of varying density and composition from here to 3.3 m ODN (Evans 1965, with
102 elevation data obtained from 2002 LiDAR/Airborne Laser Scanning (ALS) data used in this study,
103 also Figure 2). Broad saltmarsh community distribution in the upper intertidal zone comprises seasonal
104 pioneer *Salicornia europaea* at the most seaward extent, transitioning to dense *S. europaea* and
105 *Atriplex portulacoides* and *Puccinellia maritima*-dominated communities at the most landward extent
106 (Friess et al. 2012). Shore-parallel vegetation bands following the intertidal topography are based on
107 broad species-specific tolerances to physical thresholds of tidal inundation and associated
108 environmental parameters (Davy et al. 2011).

109

110 The contemporary shoreline has been heavily shaped by progressive land reclamation from at least the
111 medieval period up until the 1980s (Doody 1987). Sea defences protect large areas of agricultural land
112 (Figure 2), which are now below MSL due to disconnection from sediment supply, sediment
113 compaction and dewatering after reclamation (Dixon et al. 2008). Freiston Shore was one of the final
114 areas to be reclaimed between 1978 and 1982, extending 300 m seaward beyond the former shoreline
115 (Figure 1). Its extreme seaward position made the sea wall a focus of erosion (Doody 2013) and the
116 remaining fronting saltmarsh could not effectively attenuate incoming wave energy. Coastal defences
117 were thus realigned back to an earlier position, inundating 66 ha of formerly arable land (Figure 1c;
118 Nottage and Robertson 2005). This represented the largest realignment trial in the UK at that time.
119 Prior to breaching, over 1200 m of primary drainage channels were created within the site (Nottage
120 and Robertson 2005). The seaward defence line was breached in three locations on the 24th August
121 2002. Each breach consisted of a 50 m wide opening (determined on the basis of numerical modelling
122 (Halcrow 1999) and referred to in this study as the *breach*). Within each of the three breaches, a
123 channel (referred to in this study as the *breach channel*), 2 m wide and 1 m deep was excavated
124 (Symonds and Collins 2007a), apparently designed to be similar in dimensions to adjacent natural
125 channels at similar intertidal elevations.

126

127 [FIGURE 2 HERE]

128

129 [FIGURE 3 HERE]

130

131 **3. Materials and Methods**

132 The magnitude, and subsequent impact, of an altered hydrodynamic regime was examined in a number
133 of dimensions through the integration of four different remote sensing techniques. 2-dimensional
134 vertical aerial photography was collected by a low altitude blimp platform and fixed wing aircraft,
135 while data from a Terrestrial Laser Scanner (TLS) and airborne LiDAR/ALS provided quantitative
136 information in 3-dimensions (Table 1). These datasets were then used to quantify multiple aspects of
137 hydromorphological change: increases in breach channel width (3.1), breach channel volume (3.2),
138 creek width (3.3) and creek volume (3.4).

139

140 [TABLE 1 HERE]

141

142 **3.1 Data sources and pre-processing**

143 *3.1.1 Fixed Wing aerial photography*

144 Vertical aerial photographs of the study area were provided by the UK Environment Agency (EA) and
145 the UK Natural Environment Research Council's (NERC) Airborne Research and Survey Facility
146 (ARSF) (Table 1). Photographs were geocorrected to the British National Grid using Ordnance Survey
147 line feature data and Ground Control Points (GCPs) surveyed by RTK GPS and Total Station,
148 following Friess et al. (2012).

149

150 *3.1.2 Low altitude blimp photography*

151 Extremely high spatial resolution ($<0.1\text{m}$) aerial photography was acquired from a low altitude (<100
152 m), helium-filled (1.6 m^3) blimp platform in March 2008 to supplement the fixed-wing aerial

153 photography available for the channels in each of the three breaches. A 7.2 mega pixel digital camera
154 was mounted onto the blimp and recorded images at 60-second intervals. 1 m² marked targets in lines
155 of 5 m were laid either side of the surveyed breach channel; the centre of each target was located by a
156 Total Station survey to geocorrect the blimp image.

157

158 *3.1.3 Airborne Laser Scanning*

159 Last-return ALS (also known as airborne LiDAR) data was collected by the EA on the 16th November
160 2002 (2.5 months after breaching), and the Unit for Landscape Modelling, University of Cambridge
161 (ULM) on the 4th November 2006, on behalf of NERC ARSF (Table 1). Both surveys were conducted
162 at *ca.* MLWS to allow for maximum channel drainage and exposure. ASCII point data were converted
163 into grids (in ArcInfo 8.3) of cell size 1.0 m point spacing (2002) and 0.5 m point spacing (2006).

164

165 *3.1.4 Terrestrial Laser Scanning*

166 The use of TLS in saltmarsh environments is still in its relative infancy as a research tool (though see
167 Guarnieri et al. 2009). A ScanStation TLS (Leica Geosystems) was deployed in May 2008, conducting
168 a scan either side of the channel at the south breach (Figure 4). Point spacing was set at 8 x 8 cm at a
169 distance of 100 m, with a progressively finer spatial resolution at closer distances. The two scans were
170 georegistered together using Cyclone 5.8.1 (Leica Geosystems) (RMSE = <0.004 m) and modelled as
171 a Triangulated Irregular Network (TIN).

172

173 The TLS scan was combined with a rapid bathymetric survey to estimate below-water volume. Water
174 depth close to MLWS was recorded at 1 m intervals along the 3 established transect locations (*see*
175 *Section 3.2.1*), and at 2 additional transects, using both a portable depth sounder and levelling staff
176 (Figure 4). Water levels in the breach channels were not subjected to tidal variation during the surveys;
177 water height was measured at a known point at the start and end of each scan and showed only a ± 1
178 cm change in water height. The bathymetric transects were converted to a grid (Kriging distance
179 weighting with 3x3 Gaussian filter) in Surfer v8.0 (Golden Software), from which a coarse
180 approximation of the below-water breach channel volume was calculated.

181

182 **3.2 Breach channel data analysis**

183 *3.2.1 Mean breach channel width*

184 The width of the three breach channels was calculated using fixed-wing aerial photography, blimp
185 photography, ALS and TLS (Table 1). Breach channel width measurements from aerial photography,
186 blimp photography and ALS were taken in ArcView 3.2 (ESRI), while measurements from TLS were
187 derived using Leica Cyclone. For all techniques, breach channel width was determined at the same
188 fixed and repeatable points (from three measurements at the extreme ends and middle of each breach)
189 in all available images following breach channel construction (Figure 4). Some brief measurements of
190 breach width expansion are discussed by Symonds and Collins (2007a), though not enough
191 information is given on method or results to make a comparison with this present study.

192

193 Observations of breach channel evolution obtained at Freiston Shore were compared to equations that
194 link tidal prism to optimal breach design. Firstly, the Spring tidal prism for the Freiston Shore
195 realignment site was calculated from the volume defined by the ALS-derived surface (acquired
196 November 2002) and a plane representing MHWS over the entire 66 ha site. This equated to a Spring
197 tidal prism of 776 398 m³. The calculated tidal prism was inputted into *Equation 1*, which is derived
198 from previous observations of historical storm breaches and has been used to model optimum breach
199 width for realignment design (CIRIA 2004, Townend 2008).

200

$$W = 37.9e^{1.8 \times 10^{-6} TP} \quad [1]$$

201

202 Where W = breach width, and TP = MHWS tidal prism. Note that this equation is limited to a
203 relationship between tidal prism and breach width, i.e. assumes a fixed relationship between the two-
204 dimensional cross-sectional area of the breach and its width.

205

206 [42 HERE]

207

208 3.2.2 *Cross-sectional area of breach channels*

209 Breach channel profiles were collected from the 2002 and 2006 ALS digital elevation models across
210 the middle of each breach (Figure 4) using ERDAS Imagine 8.5 (Intergraph). Channel cross sectional
211 areas were calculated for a number of planes, relating to a) MSL (0.10 m ODN); b) bankfull
212 (equivalent to the marsh surface elevation of 3.15 m ODN), c) MHWS (3.30 m ODN); and d) the top
213 of the seawall (6.00 m ODN), relating to the full breach cross-sectional area (Figure 5).

214

215 [FIGURE 5 HERE]

216

217 *Equation 2* refers to the relationship between tidal prism and optimal inlet cross-sectional area
218 (Hughes 2002), rather than the simple breach channel width used in *equation 1* above. The
219 relationship expressed in *equation 2* is well validated for studies of the geomorphological evolution of
220 temperate saltmarsh inlets and channels (e.g. D’Alpaos et al. 2007, 2010) and has been used or
221 described in the context of managed realignment breach design (CIRIA 2004, Townend 2008). In
222 generic form, this relationship is expressed as:

223

$$224 \quad A_c = CP^k \quad [2]$$

225

226 Where A_c = equilibrium inlet cross-sectional area below Mean Sea Level, P = tidal prism and C and k
227 are an empirically derived coefficient and exponent. In this study we calculated the equilibrium cross-
228 sectional area according to a number of derivatives of this equation from previous studies (Table 2).

229

230 [TABLE 2 HERE]

231

232 3.2.3 *Volume of breach channels at bankfull stage*

233 Bankfull breach channel volume was calculated in August 2002 (the initial constructed breach channel
234 volume), shortly after breaching in November 2002 and later in November 2006 by ALS, and in May
235 2008 using TLS (south breach only).

- 236 • Initial breach channel volumes for August 2002 were derived for the south, central and north
237 breach respectively, using the initial channel dimensions described by Symonds and Collins
238 (2007a), and the breach channel length derived from ALS in November 2002 (the shortest time
239 interval available after breaching).
- 240 • ALS grids from November 2002 and 2006 were inputted into a model created in ERDAS Imagine
241 to calculate bankfull breach channel volume. For each pixel, the model calculated the elevation
242 difference between the breach floor and the average top of the breach channel (measured across the
243 middle of the channel), equating to a tidal level of ~3.15 m ODN, or 0.15 m below MHWS (Figure
244 5). Each calculated value was grouped into 10cm bins, roughly equivalent to the vertical error of
245 the ALS instrument (e.g. French et al. 2005, Hladik and Alber 2012). Error is represented by
246 calculating volumes using the average, minimum, and maximum pixel value for each bin.
- 247 • Measurements of bankfull breach channel volume were calculated from the TLS data from May
248 2008 Leica Cyclone, in the same manner as calculated for ALS.

249

250 **3.3 Tidal creek data analysis**

251 *3.3.1 Tidal creek width*

252 Geocorrected, fixed-wing vertical aerial photography collected on 10 occasions between 1999 to 2006
253 (Table 1) was used to determine change in the widths of the major creeks extending seawards from
254 each of the three breaches, and in two control creeks, located 300 - 500 m from the south breach and
255 550 - 600 m from the north breach. 40 control points were monitored along the 5 channels, at locations
256 that could be easily identified across all photo mosaics (Figure 6). The channel length sampled
257 depended on available aerial photography coverage but, where possible, channels were surveyed from
258 the outermost sea wall to the subtidal zone. This resulted in 1024 m, 1189 m and 1463 m survey
259 distances for the south, central and north creeks respectively. The south and north control creeks were
260 monitored over lengths of 1506 m and 1847 m respectively.

261

262 [FIGURE 6 HERE]

263

264 3.3.2 Tidal creek volume at bankfull stage

265 The breach channel volume model described in 3.3 was applied to the three creeks attached to the
266 breach channels that extended southeast across the shallow-sloping intertidal zone. The creeks were
267 divided into sections where the average surface elevation difference from landward to seaward was
268 <15 cm (the z-axis error of the ALS instrument). The average elevation of each channel section was
269 used to determine the bankfull plane, and volume for each was calculated as per *Section 3.2.3*.

270

271 4. Results

272 4.1 Changes in breach channel width

273 From an assumed initial width of 2 m, rapid increases in average channel width was observed at all
274 three breaches between August and November 2002, immediately after realignment (Figure 7). Lateral
275 channel expansion was greatest at the central breach, expanding from 2 m to 32 m from August 2002
276 to February 2008. Within the first 2.5 months the central breach channel increased by 19.2 m
277 (achieving 66% of the 2008 breach channel width). Expansion rates reduced between November 2002
278 and August 2003 (5.8 m in 9 months, or 7.7 m a⁻¹), and then again until August 2005 (2.2 m a⁻¹). After
279 this date no discernible breach channel width change was observed.

280

281 The south and north breach channels responded similarly to the central breach channel, though to a
282 lesser magnitude. The south and north channels expanded to 71% (16.2 m) and 70% (11.4 m) of their
283 2008 channel width respectively after 2.5 months. By August 2003 the south breach had achieved 87%
284 of the 2008 channel width, and showed little change after this time period. The north breach continued
285 to expand at a reduced rate from November 2002 to February 2004, at which point 93% of the 2008
286 breach channel width had been achieved. The reduction in expansion rate between Aug 2002 to Nov
287 2002, and Nov 2002 to 2008 was significant (t-test, $p < 0.05$) for all three breaches.

288

289 Using *Equation 1*, the increased tidal prism required a total breach width of 153.3 m, or 51.1 m per
290 breach. As of February 2008 the widths of the three breach channels (varying between 16.3 m and
291 32.0 m) were far below this theoretical equilibrium width. Instead, the optimum breach width
292 calculated by *Equation 1* most closely relates to the larger breaches in the seawall, which were
293 approximately 50 m in width each, rather than to the channel widths.

294

295 [FIGURE 7 HERE]

296

297 **4.2 Changes in breach channel cross-sectional area**

298 The rapid increase observed for the breach channel width was also reflected in other breach channel
299 geometries such as the channel cross-section, especially in the central breach channel (Figure 8). All
300 breach channels had expanded in cross-sectional area in the 2.5 months after breaching, from an
301 assumed bankfull cross-sectional area of 2 m² to 20.0 m² (central breach), 16.6 m² (south breach) and
302 10.6 m² (north breach). Between November 2002 and 2006 the central breach cross section area
303 increased to 107.6 m² (a 5280% increase from the original breach channel dimensions), while the
304 south and north breach channels expanded to 50.0 m² (2400%) and 30.3 m² (1415%) respectively.
305 These are conservative estimates of cross-sectional increase, as ALS was not able to fully penetrate
306 residual water still contained in the breach channel in 2006.

307

308 [FIGURE 8 HERE]

309

310 With a Spring tidal prism of 776 398 m³ for the Freiston Shore realignment site, *Equation 2* predicts a
311 range of total inlet cross-sectional areas depending on coefficient/exponent source (Table 3). The
312 actual cross-sectional areas of the three breaches observed at Freiston Shore were lower than
313 predictions, in some cases by 1-3 orders of magnitude, especially when compared to the MSL plane
314 (Table 3).

315

316 [TABLE 3 HERE]

317

318 **4.3 Changes in breach channel volume at bankfull stage**

319 The initial volumes for the south, central and north breach channels were calculated as 162 m³, 150 m³
320 and 120 m³ respectively. A rapid and significant increase in the channel volume between MLWS and
321 bankfull stage (see Figure 5) was observed at all 3 breaches by November 2002 (Table 4). This change
322 was greatest (in percentage terms) at the north and south breach channels, whilst a saltwater pool had
323 formed behind the former sea wall defence line at the central breach. However, by November 2006
324 this breach channel had increased by the greatest extent in both percentage and volumetric terms, by
325 an average volume change of 5744%. Over the longer term, the channel in the north breach showed
326 the least change in MLWS – bankfull volume (1446%).

327

328 [TABLE 4 HERE]

329

330 TLS extended the timeline of data collection for the channel in the south breach by a further 18
331 months. TLS calculated a MLWS – bankfull stage volume of 3649 m³, a further increase of 595 m³
332 between November 2006 and May 2008. The rapid bathymetric survey estimated a very coarse breach
333 volume from MLWS to the bottom of the breach channel of 1328 m³, giving an expected approximate
334 total breach channel volume at the south breach of 4977m³.

335

336 **4.4 Impacts of breaching on creek width seaward of the realignment site**

337 The three creeks connected to the channels in the breaches on their seaward side responded in a
338 similar fashion to the breach channels after the renewal of tidal exchange (Figure 9a). The south,
339 central and north creeks showed no measurable changes in width characteristics prior to realignment
340 (1999-2001). By August 2003 (earliest post-breach image, so not necessarily the final date of large-
341 scale change) all three creeks attached to the south, central and north breach channels had experienced
342 a large increase in their width. The overall magnitude of creek change paralleled that observed at the
343 breaches. The central creek showed the largest overall change in width (an average of 11.8 m between
344 2001 and 2006), while the south and north creeks increased in width to a lesser extent (average of 8.4

345 m and 4.0 m respectively). The central creek in particular showed a spatial pattern of creek width
346 expansion, with greater expansion closer to the breach (for example, three measured locations within
347 230 m of the breach increased by 13.9-18.7 m between 2001 and 2006) compared to measurement
348 locations further seaward (e.g. 5.7-10.3 m increase between 2001 and 2006 approximately 940-1230 m
349 away from the central breach).

350

351 [FIGURE 9 HERE]

352

353 Creek width expansion was only evident on the creeks directly attached to the breach inlet channels.
354 The control creeks (Figure 6, Figure 9b) showed no significant variation in channel dimensions before
355 or after realignment. Differences between each of the breach-impacted creek channels (south, central
356 and north) and combined 'control' channels across the time series from 1999 to 2006 were highly
357 significant ($p=0.001$) for the south and central channels, and less so for the north channels ($p=0.005$).

358

359 **4.5 Changing creek volume**

360 The north creek showed the least change in volume, increasing by 42% from 14 913 m³ to 21 181 m³
361 between November 2002 and 2006. This is in comparison to the south creek channel, which increased
362 in volume by an average of 152%, from 3291 m³ to 8285 m³. The central creek channel increased in
363 volume from an average of 11388 m³ to 48797 m³ (328% increase) by November 2006, a rate of
364 increase statistically different to the other creeks ($p<0.001$). Similar to the observations of width
365 expansion, the highest proportion of percentage change in volume of the central creek occurred within
366 the first 300 m of channel length seaward from the breach. In total, it was estimated that 47 518 – 49
367 838 m³ of material was eroded along the 3.7 km length of all three creeks, or >62000 m³ when
368 including breach channel eroded volumes also.

369

370 **5. Discussion**

371 **5.1 Impacts of an increased tidal prism on breach channel and external creek dimensions**

372 Significant hydromorphological change was experienced at Freiston Shore immediately after
373 breaching. Realignment allowed the local maximum Spring tidal prism to increase by 776 398 m³. The
374 erosional response of the breach channels was noteworthy, with the central breach channel in
375 particular increasing in width from 2 m to >32 m within 5.5 years. The breach channel response to
376 realignment was also non-linear, with 66-71% of final breach width achieved in the first 2.5 months
377 after realignment. Thus, erosional impacts were high-magnitude and short-term, with a decreasing
378 magnitude of change over the medium term (1-4 years). A number of processes are likely to have
379 contributed to the significant magnitude of breach channel erosion, and associated external creek
380 expansion. We suggest three principal reasons, related to 1) Freiston Shore's large tidal prism; 2)
381 constrained breach inlets; and 3) the establishment of water surface slopes at multiple scales.

382

383 Firstly, the macrotidal setting of The Wash means that the MSTR is large, especially relative to other
384 realignment sites in the UK. Prior to 2002, realignment trials were smaller in size and generally
385 located in areas of the United Kingdom with a smaller MSTR, such as the Essex estuaries (see Wolters
386 et al. 2005). The tidal prism during the period of breaching (August 2002) was particularly high due to
387 the coincidence with equinoctial spring tides. A larger volume of water was exchanged over a single
388 tidal cycle, equating to higher water flow velocities. Initial erosion was caused by greater water
389 current velocities than predicted through each of the breaches on the flood tide (recorded at the south
390 breach by Symonds and Collins (2007a) as reaching >2.5 m s⁻¹).

391

392 The second factor that is likely to have contributed to erosion at the breach channels was the
393 movement of a large tidal prism through a constrained inlet. While the full breaches in the sea wall
394 were modelled sufficiently according to *Equation 1*, this optimal breach width was created in the sea
395 wall largely above MHWS. The breach channels – with the bankfull elevation 0.15 m below MHWS,
396 and 3-4 m below the top of the full breach in the seawall – were the hydromorphological features that
397 most interacted with the transported tidal prism. Rapid erosion occurred after breaching as the original
398 dimensions of the breach channels (2 m) were substantially smaller than modelled breach dimensions
399 such as *Equation 1*. The breach channels were not large enough to accommodate the increased water

400 volumes, including water that would otherwise have drained laterally from marsh surfaces via sheet
401 flow but was constrained from doing so due to the remaining sea wall. This led to pooling, with the
402 realignment site remaining submerged for up to 12 hours, after the first post-breach spring tides, and
403 the ebb phase lasting 2.5 times longer than the flood (Symonds and Collins 2007a). Similarly, the
404 external creeks were originally adjusted to a much smaller tidal prism being exchanged on the fronting
405 saltmarsh only (Symonds and Collins 2007b); they could not initially cope with the increased tidal
406 prism, so eroded rapidly to accommodate the increased water volume being drained on the ebb.

407

408 Thirdly, the initial constraining effect of the breach channels, a relatively undeveloped internal
409 drainage network, and subsequent pooling at high tides established two ebb tide water surface slopes.
410 The primary water surface slope was established at high tide and the start of the ebb, and operated
411 over a large-scale, between the high elevation, hydraulically-inefficient realignment site and the lower
412 elevation, hydraulically-efficient external intertidal zone. This promoted higher ebb velocities and ebb
413 tide erosion at the breaches, while water was able to rapidly drain laterally on the external saltmarsh
414 by overland flow and the rapidly enlarged external creeks. The speed and volume of overland flow on
415 the external saltmarsh after realignment was such that ephemeral creek networks were formed to cope
416 in areas where complex creek geomorphology encouraged overbank flow on the ebb (Symonds and
417 Collins 2007b).

418

419 A secondary water surface slope was produced later in the ebb tide, as the tidal level lowered to
420 approximately the surface elevation. A water surface slope established due to the hydraulic
421 inefficiency of the internal vegetated marsh surfaces compared to drainage through the hydraulically-
422 efficient external creek channels, as measured in mature back-barrier marsh systems in N. Norfolk,
423 U.K. (Green et al. 1986). Peak velocities generated as a result of this water surface slope may surpass
424 critical thresholds beyond which sediment is entrained and leads to creek bed erosion and channel
425 incision (French and Stoddart 1992).

426

427 The two water surface slopes described generally operate across-shore, though an along-shore water
428 surface slope may also be apparent. This third slope focused water flow towards the central breach and
429 external creek, causing increased erosion here compared to the north and south breaches. The along-
430 shore water surface slope was probably established due to a subtle decrease in elevation towards the
431 central breach (Symonds and Collins 2007a, Figure 3). This observation is further supported by the
432 pattern of saltmarsh vegetation colonization after realignment: while the turbulent, low elevation
433 surface surrounding the central breach was covered by bare mud in 2003, and only pioneer *Salicornia*
434 *europaea* in 2006, the higher elevation areas away from the central breach were rapidly colonized by *S.*
435 *europaea* in 2003 and mixed mid-marsh communities by 2006 (Friess et al. 2012). Furthermore, a
436 terrestrial vegetation gradient was also apparent prior to realignment, with site photos and airborne
437 multispectral imagery showing dense, hydraulically-inefficient grass in the southwest and northeast
438 corners of the realignment site, and hydraulically-efficient bare surfaces close to the central breach
439 (Smith et al. 2007). Observations of the impact of elevation and terrestrial vegetation gradients on
440 water flow have implications for pre-realignment site preparation. Site elevations may need to be
441 levelled, and terrestrial vegetation consistently distributed or removed if the goal is to ensure evenly
442 distributed water circulation within the site.

443

444 **5.2 Comparison of breach dimensions with models of equilibrium inlet dimensions**

445 After initial rapid erosion, the breach channels stabilized at a width of 16.3 m to 32.0 m, not reaching
446 the full width of 51.1 m per breach as predicted by *Equation 1*, nor reaching the equilibrium cross-
447 sectional areas predicted by O'Brien (1931) and others using *Equation 2*. A similar observation was
448 made during the breaching of a realignment site in the hypertidal Bay of Fundy (Van Proosdij et al.
449 2010). Several reasons may account for this phenomenon. Firstly, since much of the widest part of the
450 full breach is at an elevation above tidal influence, the breach channel is eroding out to achieve the V-
451 or U-shaped channel form typical of channels in muddy, vegetated substrates (Lawrence et al. 2004,
452 D'Alpaos et al. 2006). Being at the bottom of the channel, its equilibrium width is necessarily
453 narrower than the top of the channel. Secondly, the heavy clay sea wall, and the compacted natural
454 marsh upon which it had once sat, would have a higher shear strength than natural marsh soils, in a

455 similar manner to the former agricultural soils within the realignment site (Watts et al. 2003) and for
456 other flood embankments (*sensu* Boorman and Hazelden 2012). Especially when we consider cross-
457 sectional area, *Equation 2*, designed for larger estuarine or sandy inlets may not be the most
458 appropriate to model the erosion of consolidated clay surfaces. Thirdly, when considering cross-
459 sectional area, technical limitations dictate that we may not be measuring the full breach geometry in
460 2006, due to residual water remaining in the breach, and poor water penetration by ALS (experienced
461 also by Van Proosdij et al. (2010) when monitoring realignment channel depths).

462

463 The results of this study suggest that it is crucial to address water pooling, water surface slopes and tidal
464 asymmetry in realignment implementation. This can be achieved by adequate breach design and
465 promotion of site drainage. Breach channels must be of sufficient dimensions to encourage flood
466 dominance, in which channel siltation is preferable to ebb-dominated erosion (Townend et al. 2010).
467 Water surface slopes and negative hydromorphological impacts can be controlled by breach inlet
468 design and increasing drainage capacity within the managed realignment site. Lawrence et al. (2004)
469 showed how increasing channel cross-sectional area decreases flood-ebb asymmetry and slope; at
470 Freiston Shore larger original breach channel dimensions would have decreased the potential for water
471 storage and the establishment of water surface slopes. In tandem with increased breach dimensions,
472 increased internal drainage capacity would also have lessened water surface slopes by quickly draining
473 the marsh surface and removing excess water through hydraulically efficient channels. Internal creek
474 networks may develop spontaneously in restoration sites if the site elevation is low, and the substrate
475 erodible (Vandenbruwaene et al. 2012b). However, internal surface elevations inside Freiston Shore
476 were similar to the surrounding marsh (Figure 1c) due to the short time period between reclamation
477 and restoration, and the internal substrate had higher shear strength, due to prior cultivation practices
478 (Spencer et al. 2012).

479

480 **5.3 Sedimentological and ecological impacts of water surface slopes**

481 The hydromorphological impacts observed at Freiston Shore are not divorced from other biophysical
482 processes occurring in the local area. Erosion of breach channels and external creeks released a

483 substantial volume of sediment into the local coastal zone (Rotman et al. 2008, Spencer et al. 2012),
484 calculated in this study to exceed 62 000 m³ over four years of measurements. Sediment plumes
485 emanating from the site were observed by airborne remote sensing after breaching (Smith et al. 2007),
486 smothering commercial oyster beds 1.5 km seaward of the realignment site (Dixon et al. 2008). In
487 some areas close to the breaches, surface elevation gains of almost 8 mm a⁻¹ were observed, in
488 comparison to natural rates of surface elevation change of 0.26-0.28 mm a⁻¹ just a few hundred metres
489 away from the breaches (Spencer et al. 2012). These newly deposited surfaces were raised to an
490 elevation suitable for rapid seaward saltmarsh colonization; the pioneer saltmarsh fronting Freiston
491 Shore exhibited a significant acceleration in seaward migration rates, from 3.8 m a⁻¹ in the 17 years
492 prior to breaching to 21.3 m a⁻¹ in the 4 years after breaching (Friess et al. 2012). Indeed, in the 4 years
493 after breaching it was still unclear whether the Freiston Shore managed realignment site had reached a
494 hydro-geomorphological equilibrium with the surrounding intertidal zone (Rotman et al. 2008). Thus,
495 Freiston Shore provides an important example of how hydromorphological processes can drive
496 interlinked geomorphological and ecological change in coastal wetlands.

497

498 **5.4 Hydromorphological impacts at other realignment sites**

499 While observations are scarce, realignment impacts on directly connected hydromorphological
500 features have been hypothesized more generally (French 2006). Pethick (1993) estimated that an
501 increase in tidal prism of 1x10⁶ m³ caused by a hypothetical 100 ha realignment site in the Blackwater
502 Estuary, UK, would increase the main estuary channel width by 10 m. French (2008) showed that a
503 managed realignment scenario in the Blyth Estuary, Suffolk could potentially increase flood tide
504 velocity by 20% (though realignment area/tidal prism increase was not given), with modelled impacts
505 on saltmarsh extent shown to be greater than the saltmarsh loss caused by worst-case scenarios of sea-
506 level rise over the next 50 years.

507

508 However, detailed measurements of tidal prism and creek dimensions as in this study are rare. The
509 first realignment site in the UK, Northey Island, Essex, Southeast England, increased the Blackwater
510 Estuary channel by as little as 0.4 m (no timescale given), (Pethick 1993), though this site was

511 substantially smaller (0.8 ha) in area and tidal prism than Freiston Shore, so is not strictly comparable.
512 A 21 ha estuarine realignment at Tollesbury in Essex showed little hydrological impact at the breach.
513 The breach channel was similar in initial dimensions to the channels at Freiston Shore, but increased
514 by only ~3 m immediately after breaching, almost an order of magnitude lower than the erosion
515 observed at Freiston Shore over a similar time period (Friess 2010). HR Wallingford (2002) observed
516 through bathymetric surveying some deepening of larger creeks (0.2 - 0.6 m between 1994 and 2001)
517 adjacent to the Tollesbury realignment site, Essex. It was presumed that realignment was responsible
518 as much of this increase occurred in the two years succeeding breaching, though (unlike in this study)
519 no pre-breach surveying of natural channel variation was undertaken. Tollesbury did not experience
520 large hydromorphological impacts as it is a smaller site (21ha) in a mesotidal setting (MSTR = 4.3 m),
521 representing a smaller tidal prism increase relative to Freiston Shore. Tollesbury also had a lower
522 internal surface elevation compared to the external marsh (~1 m lower on average, evidenced by poor
523 vegetation recruitment), as it was reclaimed more than 150 years ago (Garbutt et al. 2006). Both
524 factors contributed to a smaller ebb water surface slope compared to Freiston Shore.

525

526 van Proosdij et al. (2010) describe breach inlet evolution for a realignment site in the Bay of Fundy,
527 Canada. This site was only 10 ha in size, and even though it was situated in a hypertidal system, the
528 maximum tidal prism of 152 150 m³ was still much smaller than the MHWS tidal prism of 776 398 m³
529 calculated for Freiston Shore. While erosion of creeks inside the site were substantial, an excavated
530 creek 2 m wide only eroded to 12 m in width after four years, and appears to be stabilizing. Erosion
531 has been less than that of Freiston Shore in part due to a smaller tidal prism, but also because water
532 flow was not constrained through this one breach channel; once overbank flow occurred, water could
533 also pass through four other breaches. Thus, the breach channel erosion and the volume of eroded
534 sediment were substantially lower than at Freiston Shore.

535

536 **6. Conclusions**

537 Saltmarsh creation by managed realignment can lead to a significant hydrodynamic perturbation to the
538 local coastal system, with potentially substantial changes in breach channel and creek morphologies on
539 the surrounding intertidal zone as the area adjusts to the sudden imposition of a new hydrodynamic
540 regime. This study describes a large-scale experiment that was used to test geomorphological theories
541 of creek development and intertidal drainage, with important implications for the design of future
542 coastal realignment sites.

543

544 A number of factors contributed to the erosional dynamics observed at Freiston Shore. These included
545 the large increase in tidal prism; the constrained points of water exchange; and the inadequate drainage
546 capacity both inside and outside the realignment site. These factors led to the creation of seaward
547 sloping ebb tide water surfaces. These water surface slopes, and the erosion associated with them,
548 were maintained until erosion increased breach dimensions and external channel volume sufficiently
549 for the intertidal system to adjust and reduce tidal asymmetry. Although initially rapid, such erosion
550 may be constrained by the consolidated nature of the breach side substrate that is heavily compacted
551 under the weight of the breached seawall (itself made of heavily consolidated clay material), such that
552 adjustment of both breach channel width and cross-sectional area may be expected to continue at a
553 slower rate for a considerable period of time. Importantly for site design considerations,
554 hydromorphological change in response to realignment is highly non-linear, both spatially
555 (constrained to attached creek networks only) and temporally (with a high proportion of erosion
556 occurring soon after breaching), and the application of existing theoretical relationships between tidal
557 prism and tidal channel width or cross-sectional area of tidal inlets may be flawed where drainage
558 patterns are spatially complex and flow paths vary on the flood and ebb tides on high spring tides
559 within sites with multiple breaches.

560

561 The magnitude of the changes at previous realignment trials in Europe and North America were
562 substantially less than that observed at Freiston Shore, but should not give a false sense of security:
563 experience at Freiston Shore suggests that erosional impacts may increase as larger, macrotidal and
564 open coast sites are realigned, particularly if breach dimensions and drainage are not appropriately

565 engineered prior to breaching. New trials (especially those in macrotidal, open coast settings) require
566 effective understanding of how complex factors such as tidal prism, drainage and water surface slopes
567 contribute to the creation of tidal flow regimes. The aim of such understanding must be to provide a
568 more stable and predictable evolution of future realignment morphology and reduce their impact on
569 linked geomorphological and ecological processes.

570

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579

580 **References**

581 Bayliss-Smith, T.P., Healey, R., Lailey, R., Spencer, T., Stoddart, D.R., 1979. Tidal flows in salt
582 marsh creeks. *Estuar. Coast. Mar. Sci.* 9, 235-255.

583 Boorman, L.A., Hazelden, J., 2012. The use of a new portable erosion measuring device for assessing
584 the erodibility of the surface layers of flood embankments. *Soil Use Manage.* 28, 120-127.

585 Byrne, R.J., Gammish, R.A., Thomas, G.R., 1980. Tidal prism-inlet area relations for small tidal inlets.
586 *Coast. Eng. Proc.* 1, doi:10.9753/ice.v17.

587 CIRIA, 2004. *Coastal and Estuarine Managed Realignment – Design Issues*. CIRIA, London.

588 Collins, M.B., Amos, C.L., Evans, G., 1981. Observations of some sediment-transport processes over
589 intertidal flats, the Wash, U.K. In: Nio, S.-D., Shüttenhelm, R.T., Van Weering T.C., (Eds.),
590 *Holocene Marine Sedimentation in the North Sea Basin*. Blackwell Publishing, Oxford, UK. pp. 81-
591 98.

592 D'Alpaos, A., Lanzoni, S., Mudd, S.M., Fagherazzi, S., 2006. Modeling the influence of hydroperiod
593 and vegetation on the cross-sectional formation of tidal channels. *Estuar. Coast. Shelf Sci.* 69, 311-
594 324.

595 D'Alpaos, A., Lanzoni, S., Marani, M., Bonometto, A., Cecconi, G., Rinaldo, A., 2007. Spontaneous
596 tidal network formation within a constructed salt marsh: observations and morphodynamic modelling.
597 *Geomorphology* 91, 186-197.

598 D'Alpaos, A., Lanzoni, S., Marani, M., Rinaldo, A., 2010. On the tidal prism-channel area relations. *J.*
599 *Geophys. Res.* 115, F01003.

600 Davy, A.J., Brown, M.J., Mossman, H.L., Grant, A., 2011. Colonization of newly developing salt
601 marsh: disentangling independent effects of elevation and redox potential on halophytes. *J. Ecol.* 99,
602 1350-1357.

603 Dixon, M., Morris, R.K., Scott, C.R., Birchenough, A., Colclough, S., 2008. Managed realignment –
604 lessons from Wallasea, UK. *Proc. ICE Maritime Eng.* 161, 61-71.

605 Doody, J.P., 1987. Background to the Conference. In: Doody, P., Barnett, B., (Eds.), *The Wash and its*
606 *Environment*. Nature Conservancy Council, Peterborough, UK.

607 Doody, J.P., 2013. Coastal squeeze and managed realignment in southeast England, does it tell us
608 anything about the future? *Ocean Coast. Manage.* 79, 34-41.

609 Evans, G., 1965. Intertidal flat sediments and their environments of deposition in The Wash. *Quart. J.*
610 *Geol. Soc.* 121, 209-240.

611 French, P.W. 2006. Managed realignment – the developing story of a comparatively new approach to
612 soft engineering. *Estuar. Coast. Shelf Sci.* 67, 409-423.

613 French, J.R., 2008. Hydrodynamic modelling of estuarine flood defence realignment as an adaptive
614 management response to sea-level rise. *J. Coast. Res.* 24, 1-12.

615 French, J.R., Stoddart, D.R., 1992. Hydrodynamics of salt marsh creek systems: implications for
616 marsh morphological development and material exchange. *Ear. Surf. Proc. Landforms* 17, 235-252.

617 Friess, D.A., 2010. Quantifying the geomorphological impacts of managed realignment at two
618 contrasting coastal locations. *Geophemera* 109, 21-25.

619 Friess, D.A., Spencer, T., Smith, G.M., Möller, I., Brooks, S.M., Thomson, A.G., 2012. Remote
620 sensing of geomorphological and ecological change in response to saltmarsh managed realignment,
621 The Wash, UK. *Int. J. Appl. Ear. Obs. Geoinf.* 18, 57-68.

622 Garbutt, R.A., Reading, C.J., Wolters, M., Gray, A.J., Rothery, P., 2006. Monitoring the development
623 of intertidal habitats on former agricultural land after the managed realignment of coastal defences at
624 Tollesbury, Essex, UK. *Mar. Pol. Bull.* 53, 155-164.

625 Green, H.M., Stoddart, D.R., Reed, D.J., Bayliss-Smith, T.P., 1986. Saltmarsh tidal creek dynamics,
626 Scolt Head Island, Norfolk, England. In: Sigbjarnarson, G. (Ed.), *Iceland Coastal and River*
627 *Symposium, Proceedings* pp. 93-103.

628 Guarnieri, A., Vettore, A., Pirotti, F., Menenti, M., Marani, M., 2009. Retrieval of small-relief marsh
629 morphology from Terrestrial Laser Scanner, optimal spatial filtering, and laser return intensity.
630 *Geomorphology* 113, 12-20.

631 Halcrow, 1999. *Wash Banks: Hobhole to Butterwick Low; hydrodynamic, geomorphic and*
632 *environmental assessment*, Halcrow Group Ltd, Lincoln.

633 Healey, R.G., Pye, K., Stoddart, D.R., Bayliss-Smith, T.P., 1981. Velocity variations in salt marsh
634 creeks, Norfolk, England. *Estuar. Coast. Shelf Sci.* 13, 535-545.

635 Hume, T.M., 1991. Empirical stability relationships for estuarine waterways and equations for stable
636 channel design. *J. Coast. Res.* 7, 1097-1111.

637 Jarrett, J.T., 1976. Tidal prism-inlet area relationships. GITI Report 3, U.S. Army Engineer Waterways
638 Experiment Station, Vicksburg, MS. Available at [http://cirp.usace.army.mil/pubs/archive/GITI-](http://cirp.usace.army.mil/pubs/archive/GITI-Report_Number_13.pdf)
639 [Report_Number_13.pdf](http://cirp.usace.army.mil/pubs/archive/GITI-Report_Number_13.pdf) [accessed 01/01/13]

640 Ke, X., Evans, G., Collins, M.B., 1996. Hydrodynamics and sediment dynamics of The Wash
641 Embayment, Eastern England. *Sedimentology* 43, 157-174.

642 Lawrence, D.S.L., Allen, J.R.L., Havelock, G.M., 2004. Salt marsh morphodynamics: an investigation
643 of tidal flows and marsh channel equilibrium. *J. Coast. Res.* 20, 301-316.

644 Nottage, A.S., Robertson, P.A., 2005. *The Saltmarsh Creation Handbook: A Project Manager's Guide*
645 *to the Creation of Saltmarsh and Intertidal Mudflat*. RSPB, CIWEM. London.

646 Mirfenderesk, H., Tomlinson, F., 2008. Observation and analysis of hydrodynamic parameters in tidal
647 inlets in a predominantly semidiurnal regime. *J. Coast. Res.* 24, 1229-1239.

648 O'Brien, M.P., 1931. Estuary tidal prisms related to entrance areas. *J. Civ. Eng.* 1, 738-739.

649 O'Brien, M.P., 1969. Equilibrium flow areas of inlets in sandy coasts. *J. Waterways, Harbors. Coast.*
650 *Eng.* 95, 2261-2280.

651 Pethick, J.S., 1993. Shoreline adjustments and coastal management: physical and biological processes
652 under accelerated sea-level rise. *Geograph. J.* 159, 162-168.

653 Rotman, R., Naylor, L., McDonnell, R., MacNiocaill, C. 2008. Sediment transport on the Freiston
654 Shore managed realignment site: an investigation using environmental magnetism. *Geomorphology*
655 100, 241-255.

656 Rupp-Armstrong, S., Nicholls, R.J., 2007. Coastal and estuarine retreat: a comparison of the
657 application of managed realignment in England and Germany. *J. Coastal Res.* 23, 1418-1430.

658 Smith, G.M., Thomson, A.G., Wilson, A.K., Hill, R.A., Purcell, P.W., 2007. Airborne remote sensing
659 for monitoring the impact of coastal zone management. *Int. J. Rem. Sens.* 28, 1433-1435.

660 Spencer, K.L., Harvey, G.L., 2012. Understanding system disturbance and ecosystem services in
661 restored saltmarshes: integrating physical and biogeochemical processes. *Estuar. Coast. Shelf Sci.*
662 106, 23-32.

663 Spencer, T., Friess, D.A., Möller, I., Brown, S.B., Garbutt, A.G., French, J.R., 2012. Surface elevation
664 change in natural and re-created intertidal habitats, eastern England, UK, with particular reference to
665 Freiston Shore. *Wetlands Ecol. Manage.* 20, 9-33.

666 Symonds, A.M., Collins, M.B., 2007a. The development of artificially created breaches in an
667 embankment as part of a managed realignment, Freiston Shore, UK. *J. Coast. Res.* SI50, 130-134.

668 Symonds, A.M., Collins, M.B., 2007b. The establishment and degeneration of a temporary creek
669 system in response to managed coastal realignment: The Wash, UK. *Ear. Surf. Proc. Landforms* **32**,
670 1783-1796.

671 Townend, I.H., 2008. Breach design for managed realignment sites. *Proc. Inst. Civ. Eng: Mari. Eng.*
672 161, 9-21.

673 Townend, I.H., Scott, C., Dixon, M., 2010. Managed realignment: a coastal flood management
674 strategy. In: Pender, G., Faulkner, H. (Eds.), *Flood Risk Science and Management*. Wiley-Blackwell,
675 London.

676 van Proosdij, D., Lundholm, J., Neatt, N., Bowron, T., Graham, J., 2010. Ecological re-engineering of
677 a freshwater impoundment for salt marsh restoration in a hypertidal system. *Ecol. Eng.* 36, 1314-
678 1332.

679 Vandenbruwaene, W., Bouma, T.J., Meire, P., Temmerman, S. 2012a. Bio-geomorphic effects on tidal
680 channel evolution: impact of vegetation establishment and tidal prism change. *Ear. Surf. Proc.*
681 *Landforms* 38, 122-132.

682 Vandenbruwaene, W., Meire, P., Temmerman, S., 2012b. Formation and evolution of a tidal channel
683 network within a constructed tidal marsh. *Geomorphology* 151-152, 114-125.

684 Watts, C.W., Tolhurst, T.J., Black, K.S., Whitmore, A.P., 2003. In situ measurements of erosion shear
685 stress and geotechnical shear strength of the intertidal sediments of the experimental managed
686 realignment scheme at Tollesbury, Essex, UK. *Estuar. Coast. Shelf Sci.* 58, 611-620.

687 Williams, P.B., Orr, M.K., 2002. Physical evolution of restored breached level salt marshes in the San
688 Francisco Bay estuary. *Restor. Ecol.* 10, 527-542.

689 Williams, P.B., Orr, M.K., Garrity, N.J., 2002. Hydraulic geometry: a geomorphic design tool for tidal
690 marsh channel evolution in wetland restoration projects. *Restor. Ecol.* 10, 577-590.

691 Wolters, M., Garbutt, A., Bakker, J.P., 2005. Salt-marsh restoration: evaluating the success of de-
692 embankments in north-west Europe. *Biol. Cons.* 123, 249-268.

693 Zedler, J.B., Kercher, S. 2005. Wetland resources: status, trends, ecosystem services, and restorability.
694 *Annu. Rev. Environ. Resour.* 30, 39-74.

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698 * when converted to Raster

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703 ¹ Measured from 2006 ALS data, above-water volume only

704

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706 calculated from ALS surveys, August 2002 – November 2006

707 ¹ Figure in brackets denotes percentage change between time period

708 ² 2 m x 1 m (Symonds and Collins 2007a) x breach channel length = total volume

709 ³ Total volume

710 ⁴ Above-water volume only

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715

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718 Reproduced with permission from the Environment Agency

719

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722

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738 Note: position and elevation of breach for August 2002 is for illustrative purposes only.

739

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