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An integral approach to design the Roggenplaat intertidal shoal nourishment

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Keywords

Estuarine management; intertidal shoal; morphological modelling; sediment nourishment design.

Abstract

The Eastern Scheldt, a tidal basin in the southwest of The Netherlands, underwent large physical and ecological changes due to a system-wide human interference. The construction of a storm surge barrier at the seaward side and closure of the upstream branches in the 1980s resulted in intertidal flat erosion. This has far reaching consequences for the ecological functioning of these habitats, especially as foraging ground for many wader species. Therefore, a 1.3 million m³ sand nourishment is foreseen on the Roggenplaat intertidal shoal to mitigate the erosion and preserve suitable foraging habitat for waders for the coming 25 years. This paper presents an integral nourishment design approach. It consists of the following steps: (i) understanding the morphology and ecology, (ii) translation of the nourishment objective into an evaluation framework, (iii) construction of a suitability map indicating potential nourishment locations, (iv) generation of nourishment designs, (v)

26 short-term morphodynamic numerical model simulations, (vi) estimation of the long-term shoal
27 development using a simplified approach, (vii) integral evaluation leading to the preferred design.
28 This integral approach resulted in a design that is expected to fulfill the Roggenplaat nourishment
29 objective, accounting for ecological, morphological, economical and technical aspects. This
30 integrated approach could form a basis for future intertidal shoal nourishment designs worldwide.

31

32 **1. Introduction**

33 Intertidal flats are essential habitats of estuaries and other low energy marine environments. They
34 are distributed widely along coastlines worldwide, accumulating fine-grain sediments on gently
35 sloping beds, forming the basic structure upon which coastal wetlands build. Intertidal flats are
36 found in e.g. in the Yangtze estuary, China (De Vriend et al., 2011; Zhu et al., 2017), San Francisco
37 Bay, USA (Van der Wegen et al., 2017) and the Eastern and Western Scheldt, The Netherlands (De
38 Vriend et al., 2011; De Vet et al., 2017). Two types of intertidal flats can be distinguished: intertidal
39 shoals, which are surrounded by tidal channels, and fringing flats, which are attached to the shore.
40 The physical structure of intertidal flats is diverse and ranges from mobile, coarse sand
41 environments on more wave-exposed coasts to stable, fine-sediment mudflats in more sheltered
42 environments. Its morphology is a complex outcome of tides, waves, sediment properties and
43 ecological processes (Le Hir et al., 2000; Friedrichs, 2011; De Vet et al., 2018).

44

45 Intertidal habitats are highly productive and diverse components of shallow coastal ecosystems
46 providing essential ecosystem functions and services (Barbier et al. 2011; Boerema & Meire, 2017).
47 They are worldwide protected by international conventions and legislations, e.g. the Ramsar
48 convention for the protection of migratory birds or the European Natura2000 legislation. Intertidal
49 flats, along with seagrass beds, saltmarshes and mangroves constitute coastal wetlands, a vital part
50 of the coast. The intertidal flats form a buffer zone between deeper channels and the higher-lying
51 salt marshes or mangroves, protecting the latter by dissipating wave energy (Bouma et al., 2016).

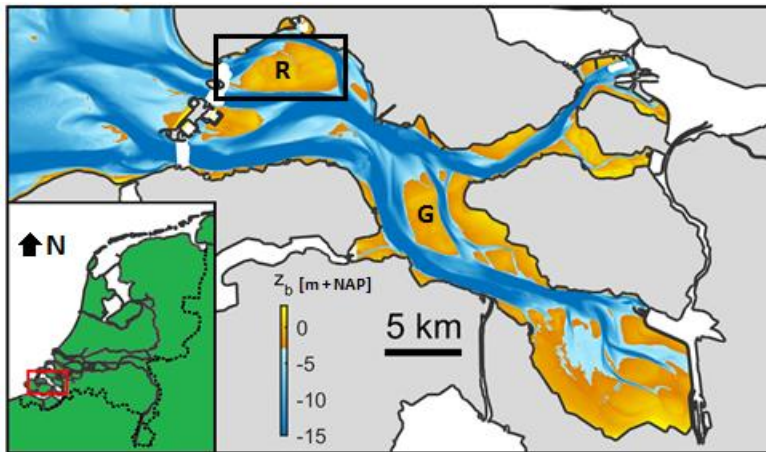
52

53 Despite their services and protection, intertidal flats are under pressure from human-induced
54 changes that affect their quantity and quality (Lotze et al. 2006; Airoldi and Beck, 2007). At a global
55 scale, climate change and sea level rise on the one hand, and development of coastal societies on
56 the other hand, squeeze the intertidal coastal strip. At the larger scale, embankments, building of
57 barriers and dredging activities have affected the hydrodynamics, morphology, biodiversity and
58 ecological value of the intertidal flats (Thrush et al., 2004; Cozzoli et al., 2017). At the scale of an
59 individual flat, land reclamation, artificial saltmarsh development and dike reinforcements have
60 provoked considerable area losses.

61

62 The Eastern Scheldt, a tidal basin in the southwest of The Netherlands (Figure 1), is a good example
63 of a coastal system that underwent large physical and ecological changes due to a system-wide
64 human interference. The completion of the Eastern Scheldt storm surge barrier at the seaward side
65 and the closure of the upstream branches in 1986 led to a decrease in tidal velocity resulting in a
66 decrease in sediment transport from the channels onto the intertidal flats. As wave-induced erosion
67 continues, the net effect is erosion and flattening of the intertidal flats (Louters et al., 1998; De Vet
68 et al., 2017). It is expected that by 2100 less than half of the original intertidal flats in the Eastern
69 Scheldt will remain (De Ronde et al., 2013). The loss and flattening will have far reaching
70 consequences for the ecological functioning of these habitats (Cozzoli et al, 2017), especially as a
71 foraging ground for many wader species for which the Eastern Scheldt is of international importance.

72



73



74

75 *Figure 1. Upper panel: the Roggenplaat intertidal shoal (R, black box) in the Eastern Scheldt tidal basin located*
 76 *in the southwestern part of The Netherlands. Also the Galgeplaat intertidal shoal (G) is indicated in this panel.*
 77 *The bathymetry is based on 2013 data. Lower panel: 2014 aerial photo of the Roggenplaat (in false colors)*
 78 *(courtesy Edwin Pree, Rijkswaterstaat) with the location of the transect shown in Figure 3 (circle is the start of*
 79 *the transect).*

80

81 As a measure to mitigate the loss of intertidal areas in the Eastern Scheldt, Rijkswaterstaat (the
 82 executive agency of the Ministry of Infrastructure and Water Management) started with pilot tidal
 83 flat nourishment experiments. Compared to beach and shoreface nourishments, a common practice
 84 along the Dutch coast, nourishment of intertidal flats in estuarine or coastal environments is
 85 relatively unexplored. A first small pilot was realized in 2008 on the Galgeplaat intertidal shoal
 86 (location indicated in Figure 1). This pilot showed that intertidal flat nourishments have the potential

87 to effectively counteract the negative ecological consequences of erosion (Van der Werf et al., 2015).
88 Monitoring showed that the nourished sediment was relatively stable with an expected nourishment
89 life-time of tens of years. The benthic macrofauna largely recovered after three years, especially in
90 terms of species richness and total biomass. Community composition, however, still differed
91 compared to nearby undisturbed sites (Van der Werf et al. 2015). Recovery of the benthic
92 macrofauna on the nourishment was not uniform, with slower recovery and lower biomass values
93 on the higher dryer parts and faster recovery with higher biomass values on the lower, wetter parts
94 of the nourishments. This was also reflected in the use by birds of the nourishment, with lower
95 numbers of foraging birds on these higher parts (Van der Werf et al., 2015).

96

97 Following this pilot and other studies, it was decided to fully implement this nourishment strategy to
98 mitigate the erosion of the intertidal flats, and to nourish the Roggenplaat intertidal shoal (Figure 1)
99 with 1.3 million m³ of sand, a tenfold of the Galgeplaat pilot nourishment. The planned borrow area
100 is located in the Roompot tidal channel south of the Roggenplaat. The sediment in the borrow site
101 contains low slit percentages (0.5-3.0%) and has a median grain-size between 0.18-0.40 mm
102 (Vönhögen-Peeters et al., 2013). The Roggenplaat shoal was chosen as it is an important foraging
103 area for wading birds. It suffers severely from erosion and is probably bound to lose most of its
104 foraging function over the coming decades (De Ronde et al., 2013). It is expected that the sand
105 nourishment will be executed in 2019-2020. The main aim is to ensure that in 2035 the bird foraging
106 function of the Roggenplaat is at least equal to the reference year 2010, thus compensating for
107 future tidal flat erosion and sea level rise (SLR) for a 25-year period.

108

109 This paper describes an integral approach for designing the nourishment of the Roggenplaat shoal. It
110 does not consider (effects of) sand extraction. The design process consists of the following 7 steps:

- 111 1. Characterization of the Roggenplaat morphology and ecology based on existing knowledge
112 and new monitoring data.

- 113 2. Translation of the main nourishment objective into an evaluation framework.
- 114 3. Construction of a suitability map indicating potential nourishment areas, based on
115 morphological, ecological, economical and technical considerations.
- 116 4. Generation of nourishment alternatives and designs.
- 117 5. Calculation of the nourishment impact on short-term hydro-morphodynamics using a
118 Delft3D numerical model.
- 119 6. Prediction of the long-term future shoal development using a simplified approach.
- 120 7. Integral evaluation of the nourishment alternatives leading to the preferred design.

121

122 The paper is organized as follows. Section 2 describes the Roggenplaat morphology and ecology (i.e.
123 Step 1). The approach to design the Roggenplaat nourishment is described in Section 3, including the
124 evaluation framework and suitability map (Steps 2 and 3). This section continues with the Delft3D
125 numerical model set-up and the simplified approach to predict the long-term intertidal area
126 development. Section 4 describes and evaluates three nourishment alternatives, followed by the
127 generation and evaluation of three more detailed designs (Steps 4-7). The results are discussed in
128 Section 5. Section 6 presents the conclusions, and the general lessons learned from this study are
129 given in Section 7.

130

131 **2. Morphological and ecological characterization of the Roggenplaat**

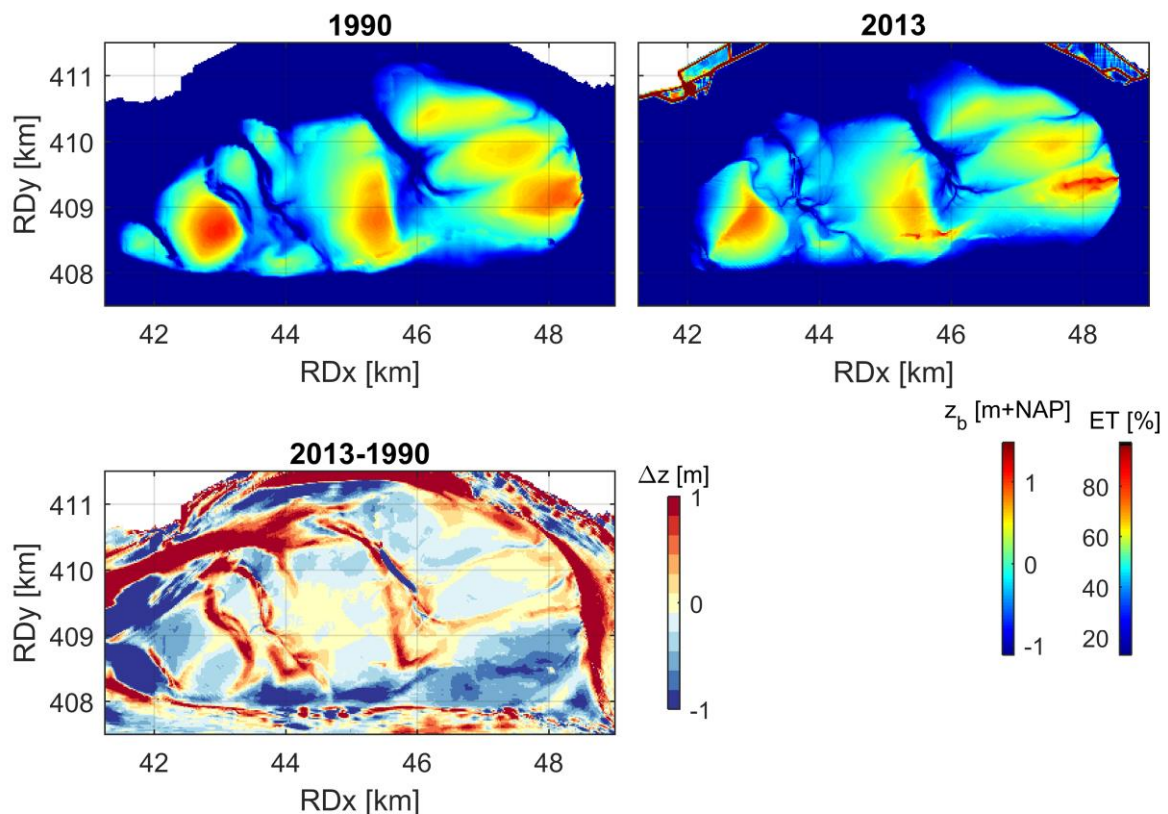
132 The Roggenplaat is the largest intertidal shoal of the Eastern Scheldt, the Netherlands. It has a
133 surface area of 14.6 km² between mean high water and mean low water (situation 2013). The
134 Roggenplaat contains two northwest-southeast orientated drainage channels of which the eastern
135 one is more than 100 m wide, see Figure 2. Before the Eastern Scheldt storm surge barrier was
136 constructed (1986), sediment accreted on the Roggenplaat (Louters et al., 1998). However, the
137 Roggenplaat eroded on average 0.5 cm/year vertically after the completion of this barrier (De Ronde
138 et al., 2013). As also visualized in Figure 2, the area with more than 50% exposure time (bed level, $z_b >$

139 NAP¹-0.04 m) decreased from 751 ha in 1990 to 615 ha in 2013. The area with more than 80%
 140 exposure time ($z_b > \text{NAP} + 1.02 \text{ m}$) was decreased from 5 ha in 1990 to 4 ha in 2013. The areas with
 141 50-80% exposure time are important because they provide sufficient time for wader species to
 142 search for and feed on macrobenthic animals.

143

144 In Figure 3 the measured morphological evolution along a transect is visualised. The largest erosion
 145 rates occur in the south of the Roggenplaat. De Vet et al. (2018) showed that the sediment transport
 146 on the Roggenplaat is mainly in north-eastern direction, which is in line with the dominant wind (and
 147 thus wave) direction. This main sediment transport direction caused the high ridges on northern part
 148 of the shoal not purely to decrease in elevation but also to propagate in north-eastern direction, see
 149 also Figure 3.

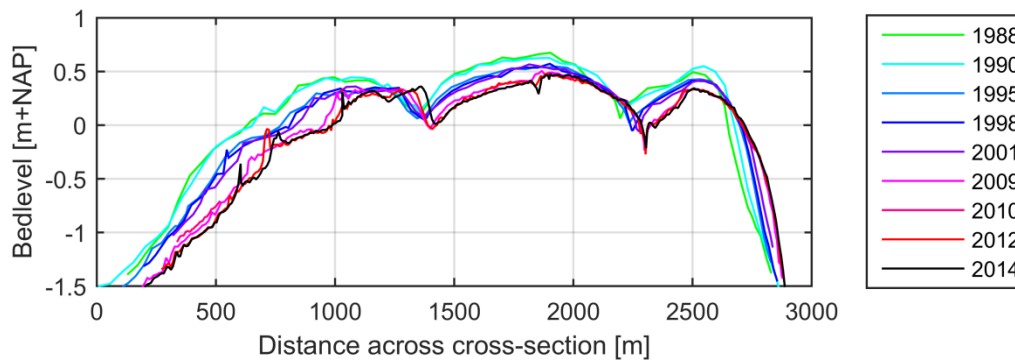
150



151

¹ NAP is the Dutch vertical datum close to mean sea level.

152 Figure 2. Top: bathymetry maps of the Roggenplaat for the years 1990 and 2013. Both the color scale in meters
 153 as in exposure times (ET) are provided. Bottom: bathymetry difference map. The bathymetry maps are a
 154 combination of single beam, multibeam and LiDAR measurements (courtesy data Rijkswaterstaat).
 155



156
 157 Figure 3. The morphological evolution of a cross-section of the Roggenplaat (courtesy data Rijkswaterstaat).
 158 The location of the transect is indicated in Figure 1, the transect starts at the south.
 159

160 The sediment on the Roggenplaat can be characterized as fine sand with an average median grain
 161 size of $210 \pm 3 \mu\text{m}$ (based on 113 sampling locations distributed over the entire shoal, measured in
 162 2016). The spatial distribution on the Roggenplaat shows somewhat coarser sediment in the western
 163 part. Locally, in the vicinity of oyster reefs (*Crassostrea gigas* mixed with blue mussels *Mytilus edulis*),
 164 the sediment is more silty (max. 33% of silt; silt is defined as sediment with grain size smaller than $63 \mu\text{m}$),
 165 but on average silt content is low (4%). No correlation between sediment composition and
 166 exposure time was observed. Oyster reefs cover about 3% (45 ha) of the Roggenplaat, and occur in
 167 the north-eastern part and near the two drainage channels. Ridges of bivalve shells occur along the
 168 southern edge, visual as the whitish areas in Figure 1.

169
 170 The benthic macrofauna on the Roggenplaat consists mainly of polychaetes, bivalves and
 171 crustaceans. In 2016, 81 taxa were observed in total (based on 113 sampling locations), with on
 172 average 11 ± 0.5 taxa per locations. The average abundance was $5026 \pm 615 \text{ ind.m}^{-2}$, the average
 173 biomass $31 \pm 4 \text{ g AFDW.m}^{-2}$. The most common species were the polychaete *Scoloplos armiger*, the

174 amphipod *Urothoe poseidonis*, and the bivalve *Limecola balthica*. In terms of biomass bivalves
175 dominate, with the cockle *Cerastoderma edule* as the most important species (35% of the total
176 biomass). (Ysebaert et al., 2016)

177

178 The Roggenplaat is one of the most important foraging areas for wader species in the Eastern
179 Scheldt, with up to 20,000 waders feeding here at low tide during winter and migration periods (e.g.
180 Arts et al., 2017). The most common species include Dunlin (*Calidris alpina*), Bar-tailed Godwit
181 (*Limosa lapponica*), Oystercatcher (*Haematopus ostralegus*), Eurasian Curlew (*Numenius arquata*),
182 Grey Plover (*Pluvialis squatarola*), Sanderling (*Calidris alba*) and Knot (*Calidris canutus*).

183

184 The Roggenplaat is an important resting area for common seals (*Phoca vitulina*) and grey seals
185 (*Halichoerus grypus*). In the season 2015/2016 a maximum of 89 common seals and 7 grey seals
186 were counted at one occasion (Arts et al., 2017). The seals mainly occur along the steep banks of the
187 two drainage channels.

188

189 The Eastern Scheldt is an important area for the cultivation of mussels and oysters, and along the
190 north side and south side of the Roggenplaat 25 mussel bottom-culture plots are located. The total
191 surface of these culture plots is 427 ha. The plots cover partly the intertidal zone and partly the
192 shallow subtidal zone, but nowadays only the subtidal part is used for growing mussels.

193

194 **3. Methods**

195

196 **3.1 Design approach**

197 The main objective of the 1.3 million m³ Roggenplaat sand nourishment is to maintain the bird
198 foraging function for 25 years in light of future tidal flat erosion and SLR. The nourishment volume is
199 based on the expected loss of intertidal area with a 50-80% exposure time between 2010 and 2035

200 (De Ronde et al., 2013). The design process aims to find the nourishment configuration (height,
201 location, geometry) that best fulfills this objective.

202

203 First, the nourishment objective was translated into an evaluation framework, and a suitability map
204 indicating potential nourishment areas was constructed. Second, the preferred nourishment
205 alternative was selected from three alternatives based on different operating principles. Third, the
206 preferred alternative was detailed, resulting in three nourishment designs of which one was selected.
207 The selections were based on the evaluation framework, fed by system understanding, (Delft3D)
208 numerical model simulations of short-term hydro-morphodynamics and a simplified approach to
209 estimate the long-term intertidal area development.

210

211 **3.2 Evaluation framework**

212 The evaluation framework serves two goals. It is set up to systematically and objectively assess and
213 compare effectiveness and impact of the nourishment designs. Also, it plays a process role as a
214 shared guiding structure in the cooperation among multidisciplinary researchers and as a means of
215 communication with stakeholders. The evaluation framework was constructed in the first project
216 phase during two workshops with scientists and a selection of stakeholders.

217

218 The key indicator reflects the bird foraging function of the Roggenplaat. The Eastern Scheldt is an EU
219 Bird Directive (2009/147/EC, site code NL3009016) designated area for 14 migratory bird species, all
220 but one are wading birds. The foraging function is determined by three factors: 1) the size of the
221 intertidal area, 2) the exposure time, i.e. the time the intertidal area is accessible for foraging, so not
222 covered with water, and 3) the food availability and food quality. Although there are variations
223 between the bird species, the intertidal area (IA) with 50-80% exposure time (IA50-80%) was shown
224 to be most important for the Eastern Scheldt as it enables birds to feed longer which is crucial during
225 the winter months (De Ronde et al., 2013). Hence this was defined as the key indicator. In 2010,

226 IA50-80% was equal to 606 ha and is predicted to decrease to 421 ha in 2035 with the autonomous
227 development. Therefore, a nourishment design is considered suitable when the IA50-80% in 2035 is
228 at least 606 ha.

229 The food availability and food quality represented by the benthic community are related to exposure
230 time, but also to other factors such as hydrodynamic conditions and sediment composition (Cozzoli
231 et al., 2013). As insufficient knowledge was available for quantification, this aspect was included
232 qualitatively through expert judgement in the evaluation framework.

233 Two additional support indicators were defined. The footprint is the area where existing benthic life
234 will be destroyed by the placement of nourishment sand. A minimal footprint is considered positive,
235 even though no quantitative target is set. The nourishment circumference is the length of the
236 waterline which is a possible hotspot for foraging birds. A longer nourishment circumference is
237 considered positive, but again no quantitative target is set.

238 Exclusion criteria for the nourishment location resulting in a suitability map (see next paragraph, 3.3)
239 are also part of the evaluation framework. Finally, the construction costs were considered in a
240 relative sense.

241

242 **3.3 Suitability map**

243 The nourishment suitability map distinguishes between areas that are considered suitable and not
244 suitable to nourish with sand (Figure 4G). It excludes areas based on a combination of economical,
245 ecological, morphological and technical considerations, as explained below.

246

247 *Commercial mussel beds*

248 There are several commercial mussel beds on the northern and south-eastern side of the
249 Roggenplaat tidal flat. Nourishments can have negative impacts on mussels in two ways. First, fine
250 sediments that wash out from the nourished sediment may lead to an increase in suspended

251 sediment concentrations, which might reach the mussel culture plots, which in turn can lead to a
252 decrease in the food intake by the mussels. Second, nourishments can cause undesired sediment
253 coverage of the mussel beds during the construction phase (mainly fines) and thereafter (mainly
254 sand).

255

256 During the construction phase, nourishment techniques will be used that restrict the amount of fines
257 released from the nourished sediment, for instance by spouting the sediment onto the tidal shoal
258 during low tide only. Also suspended sediment concentrations will be monitored continuously during
259 nourishment operations, and eventually construction operations will be stopped when suspended
260 sediment concentrations exceed a threshold value. It is expected that suspended sediment
261 concentrations will not increase a lot, because of the relatively coarse sediment (D_{50} between 0.18
262 and 0.40 mm) that will be used for the nourishment, containing very little silt (0.5-3.0%). The
263 possible, temporary increase in suspended sediment concentrations is taken care of during the
264 nourishment construction and monitoring, and not part of the design process.

265

266 Sessile benthos organisms such as mussels and oysters can cope with sediment deposition of only 1-
267 2 cm (Essink, 1999). Based on experience with the Galgeplaat nourishment (Van der Werf et al.,
268 2015), the migration of Roggenplaat bedforms (Figure 3) and computations of the initial
269 morphological development (Section 4.4), we estimate that the nourishment sand will move with a
270 rate of ~1-10 m/year in the dominant, northern/northeastern, transport direction. This corresponds
271 to a maximum distance of 200 m during a typical 20 year nourishment lifetime. A buffer of 200 m
272 was added to further limit the risks, leading to the exclusion of areas within 400 m from the mussel
273 beds (Figure 4A). An area near the two drainage channels was also excluded (see further), as to
274 diminish the possible outflow of fines through these channels in the direction of the mussel plots.

275

276 *Resting areas of seals*

277 Harbour seals and grey seals often rest and give birth to pups at the banks of the two main drainage
278 channels of the Roggenplaat (Arts et al., 2017), see Figure 4B. Dutch legislation allows approaching
279 seals up to a distance of 1200 m. Following this rule would cancel out a too large part of the
280 Roggenplaat as potential nourishment location. A field experiment was conducted to find a more
281 workable distance, still respecting the seals resting areas (Dekker, 2016). This experiment
282 demonstrated that seals raised their heads at ≈ 700 m distance from a small group (2 to 4)
283 approaching researchers. At distances of ≈ 400 m seals started to move. Based on this experiment it
284 was chosen to exclude areas within 600 m from the centre point of the two main resting areas
285 (Figure 4B).

286

287 *Oyster reefs*

288 Oyster reefs, mixed with blue mussels, are present on the Roggenplaat. They have a relatively high
289 species richness and biomass. Furthermore, these reefs are able to protect the underlying and
290 surrounding sediment against erosion (Wallis et al., 2015). Therefore, the oyster reefs were
291 excluded from the suitability map (Figure 4C).

292

293 *Tidal drainage channels*

294 The two main tidal drainage channels are not suitable for nourishments. They will mainly discharge
295 the nourished sediment away from the tidal flat into the channel, reducing the nourishment lifetime
296 and possibly affecting the nearby commercial mussel beds. Therefore, the two main tidal creeks,
297 defined through the mean low water line and a 150 m buffer zone were not included in the
298 suitability map (Figure 4D).

299

300 *Erosive areas*

301 In order to avoid a quick erosion of the nourished sand, it was decided to exclude areas with high
302 erosion rates (>14 mm/year based the 1990-2010 linear trend, De Ronde et al., 2013), see Figure 4E.

303 The erosion of the southern edge of the Roggenplaat was already present in the 19th century and is
304 not so much related to the construction of the storm surge barrier in 1986 (De Vet et al., 2018).

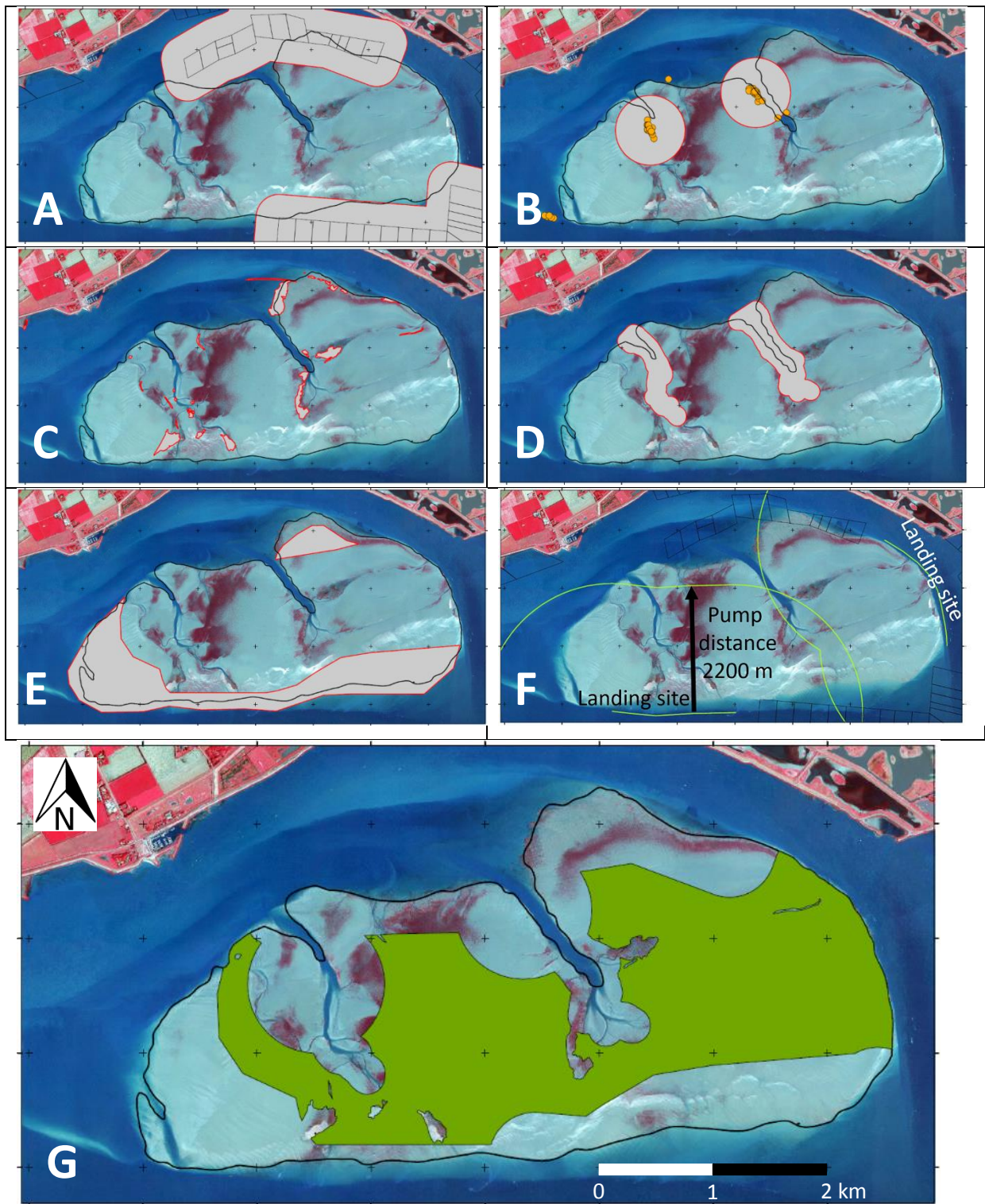
305

306 *Feasibility nourishment construction*

307 The trailing suction hopper dredger can approach the Roggenplaat only from two sites, related to
308 the navigation depth of the surrounding channels and the presence of the commercial mussel beds.

309 From here the sediment pumping distance (without the need for a booster) is about 2200 m. This
310 means it is technically feasible to nourish almost the complete Roggenplaat (Figure 4F).

311



312

313 *Figure 4. A-G: Roggenplaat areas excluded as potential nourishment areas. A: 400 m away from commercial*
 314 *mussel beds (grey lines). B: 600 m away from the two main seals resting areas (orange dots: observed seals). C:*
 315 *oyster reefs. D: 150 m away from the two main tidal creeks. E: highly erosive areas. F: nourishment to be*
 316 *constructed within 2200 m pumping distance from the two possible landing sites. G: in green the resulting area*
 317 *suitable for nourishment.*

318

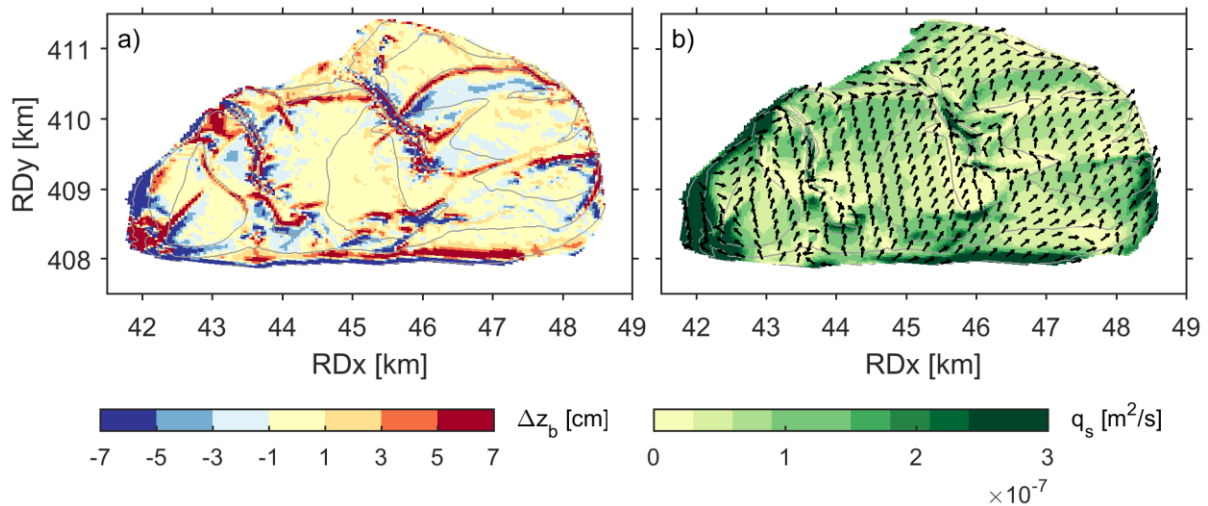
319 **3.4 Delft3D numerical modelling**

320 The nourishment impact on hydrodynamics (waves and current), sand transport and short-term (1
321 year) morphological change was evaluated with a 2DH (two-dimensional, depth-averaged) Delft3D
322 morphodynamic model (Lesser et al., 2004). The computational domain covers the western part of
323 the Eastern Scheldt with a maximum grid size resolution of 30 m at the Roggenplaat. The model is
324 forced by time series derived from nesting within larger models. Wind and offshore wave forcing
325 were based on measured time-series. The single-fraction ($D_{50} = 0.21$ mm) sand transport was
326 computed solving the advection-diffusion equation for suspended sand concentrations in
327 combination with the Van Rijn (2007a, b) transport formulas. See De Vet et al. (2018) for more
328 details on the model set up.

329

330 The model was validated based on field measurements using a 1-month velocity data set at 16
331 locations and a 2-months wave height data set at 3 locations on the Roggenplaat. The root-mean-
332 squared deviations ranged between 3.5-7 cm/s and 4.2-7.0 cm, respectively (see De Vet et al, 2018
333 for more details). Figure 5 shows the computed net sand transport rates and bed level change for
334 the May 2015 forcing with wind conditions representative for the 2011-2015 period. This
335 corresponds to 1 morphological year using a scale factor (MorFac) of 12. The net transport is
336 predominantly in north-eastern direction and the higher parts of the Roggenplaat migrate in the
337 same direction, in accordance with the observations (Figure 3). The computed bed level changes are
338 larger than observed due to model artefacts. Therefore, we used the Delf3D model to evaluate the
339 nourishments in a relative sense (compared to the no-nourished case), in conjunction with system
340 understanding and expert judgement.

341



342

343 *Figure 5. Computed bed level changes (a) and net sand transport rates (b) on the no-nourished Roggenplaat*
 344 *during 1 year based on the May 2015 forcing and a morphological factor of 12. Only values above MLW (mean*
 345 *low water) are shown for clarity reasons. Red colors in (a) indicate accretion, blue colors erosion. The net sand*
 346 *transport vector field (b) was thinned with a factor of 30. The arrows in (b) only indicate the net sand transport*
 347 *direction, not the magnitude.*

348

349 **3.5 Simplified approach to predict future loss of intertidal area**

350 The Delft3D model is capable of predicting the short-term nourishment impact in a qualitative sense,
 351 but less suited to predict the long-term (i.e. 25-year) evolution of the targeted 50-80% exposure
 352 time area. This is because the complex morphodynamic interaction processes cause a relatively large
 353 model uncertainty and long computation times.

354

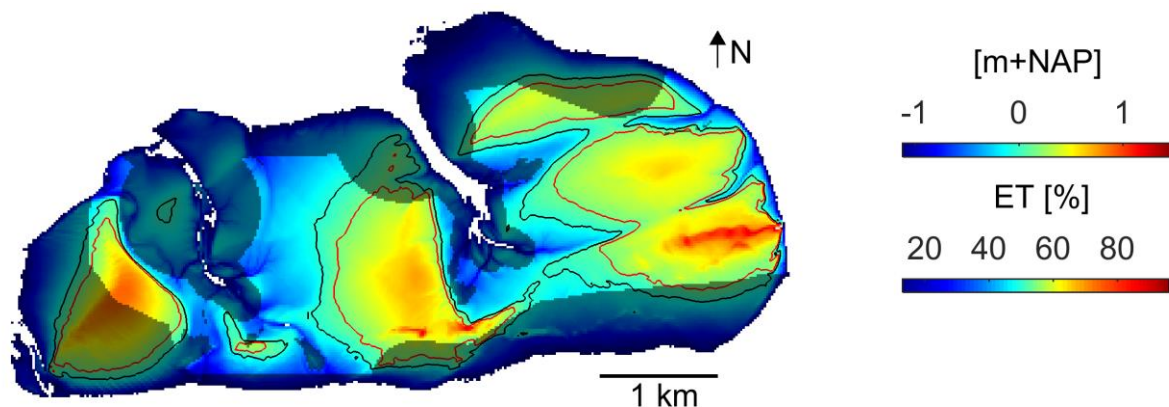
355 Therefore, we investigated the evolution of the 50-80% exposure time area using a simplified
 356 approach. The main assumptions are that i) the average lowering rate of the Roggenplaat is spatially
 357 uniform, ii) the relative (with respect to mean sea level) erosion of the Roggenplaat is due to a
 358 constant SLR and bed level erosion rate, iii) the bed level erosion rate is not affected by the
 359 nourishment. The first assumption is supported by the evolution of the Roggenplaat hypsometry
 360 between 1990 and 2013 (see De Vet et al., 2017). The Delft3D model results showed that the
 361 nourishment only has a local impact on the morphodynamics (see Figure 9), supporting the third

362 assumption. We take a 0.4 cm/year future SLR (KNMI, 2015) and a 0.5 cm/year erosion rate based
363 on the observed 1990-2010 evolution (De Ronde et al., 2013). These are possibly conservative
364 estimates, as the current SLR is 0.2 cm/year and the erosion seems to have slowed down since
365 around 2010 (see e.g. Figure 3). We have preferred the 1990-2010 erosion trend over the 2010-2014
366 trend as it is based on more data points over a longer period. The erosion could be temporary
367 slowed down between 2010 and 2014, similar to the period 1995-2001.

368

369 Under these assumptions, we predicted the evolution of the no-nourished/nourished Roggenplaat
370 by shifting the bathymetry vertically down with a rate of 0.9 cm/year (0.4 cm/year future SLR + 0.5
371 cm/year erosion rate). From this we derived the required development of the 50-80% exposure time
372 area, and other areas as well. The 0.9 cm/year rate implies 20 cm relative erosion between 2013
373 (latest bathymetry) and 2035 (target year). The nourished sand is most effective when placed in
374 regions that will fall below the 50-80% exposure time area in 2035, if no measures are taken. This
375 implies that nourishments are most effective below the current 50% exposure time elevation, (NAP -
376 0.04 m) plus the expected 20 cm erosion, thus below NAP +0.16 m (Figure 6). Section 4 elaborates
377 further on how this simplified approach was used to design and evaluate the nourishment design.

378



379

380 *Figure 6. Roggenplaat 2013 bathymetry with 50% exposure time contour lines (black) plus the expected 20 cm*
381 *relative erosion between 2013-2035 (red). The shaded regions are excluded from nourishing based on the*
382 *suitability map (see Figure 4).*

383

384

385 **4. Roggenplaat nourishment design**

386

387 **4.1 Nourishment alternatives**

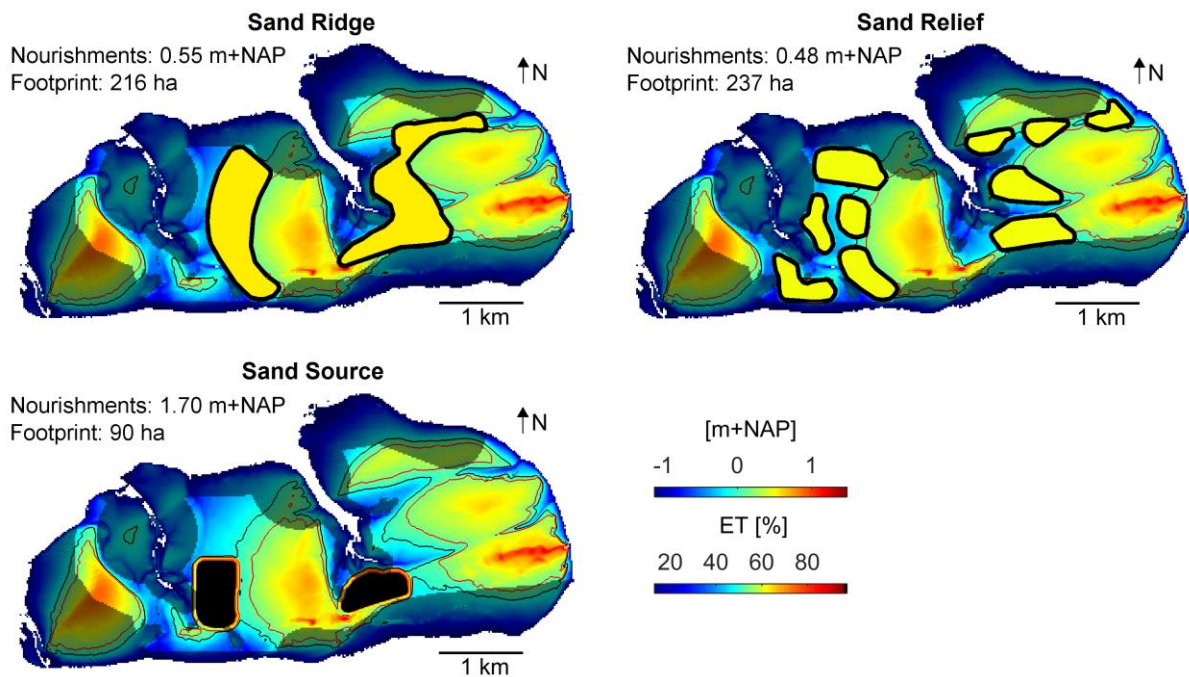
388 The total nourishment volume is fixed (see Section 3.1); the nourishment design variables are
389 location (restricted by the suitability map and anticipated future bed levels, Figure 6), height and
390 shape. With this in mind we generated three nourishment alternatives with different design
391 principles (Figure 7):

392 1. *Sand Ridge*. Two ridges of sand (top at NAP +0.55 m) that directly increase the 50-80%
393 exposure time area.

394 2. *Sand Relief*. Ten nourishment elements (top at NAP +0.48 m) that directly increase the 50-
395 80% exposure time. The sheltered areas between the elements are intended to encourage
396 ecological recovery.

397 3. *Sand Source*. Two high (NAP +1.7 m) sediment sources to feed the Roggenplaat naturally,
398 and with a relatively small footprint to have a minimal initial ecological impact.

399



401

402 *Figure 7. The nourishment alternatives Sand Ridge, Sand Relief and Sand Source on top of the 2013 bathymetry*
 403 *with 50% exposure time contour lines (black) plus the expected 20 cm relative erosion between 2013-2035 (red).*
 404 *The shaded regions are excluded from nourishing based on the suitability map (see Figure 4). The Sand Source*
 405 *nourishment has a black colour because its height is off scale.*

406

407 **4.2 Evaluation alternatives**

408 Table 1 shows the characteristics and performance indicators (based on the evaluation framework
 409 described in Section 3.2) of the nourishment alternatives, as well as of the no-nourishment
 410 reference scenario. The key indicator is the intertidal area with a 50-80% exposure time in 2035. If
 411 this number is smaller than the 2010 value, the nourishment design is rejected. The other two
 412 indicators are the nourishment footprint (smaller footprint is considered positive, because of
 413 potentially faster ecological recovery) and the nourishment circumference (longer circumference is
 414 considered positive, because it means more feeding hotspots for wading birds). These three
 415 indicators, combined with expert judgement, are used to score the ecological and morphological

416 aspects of the nourishment alternatives. Finally, the relative construction costs were estimated by a
417 contractor.

418

419 The Sand Source alternative, although having a small footprint and the lowest costs, appears to be
420 an unsuitable design. By the year 2035 the area with 50-80% exposure time in this alternative will
421 have fallen to 442 ha, which is 164 ha less than targeted for. These intertidal areas were computed
422 using the simplified model approach as described in Section 3.5. This ignores effects of horizontal
423 sediment spreading (see Section 3.3). Even with a 200 m radial sand spreading (upper limit), the
424 Sand Source alternative does not result in a sufficient increase of intertidal area with 50-80%
425 exposure time. The dynamics are too low to anticipate on natural sediment spreading and not to put
426 the sediment at the right place immediately.

427

428 The Sand Ridge and Sand Relief alternatives are expected to meet the required 606 ha 50-80%
429 exposure time area until 2035. The Sand Ridge alternative consists of fewer elements than the Sand
430 Relief alternative and is consequently less expensive to construct. The morphological development
431 (somewhat stronger sediment spreading) and longer sand nourishment circumference of the Sand
432 Relief alternative are expected to provide better ecological boundary conditions than the Sand Ridge
433 alternative. Therefore, the Sand Relief nourishment alternative was selected as the preferred
434 alternative, and was studied in more detail.

435

436 Table 1. Characteristics, performance indicators and scores of the Roggenplaat shoal nourishment alternatives
 437 and designs, and of the reference, i.e. no-nourishment scenario. The key performance indicator, the area with
 438 50-80% exposure time, was estimated using a simple modelling approach. The scores on the morphological
 439 aspect were based on this key indicator and on expert judgment using Delft3D numerical model simulations,
 440 amongst other things. The ecological scores followed from an expert judgement based on the area with 50-80%
 441 exposure time, the nourishment footprint, the nourishment circumference, and other considerations. The
 442 relative construction costs were estimated by a contractor.

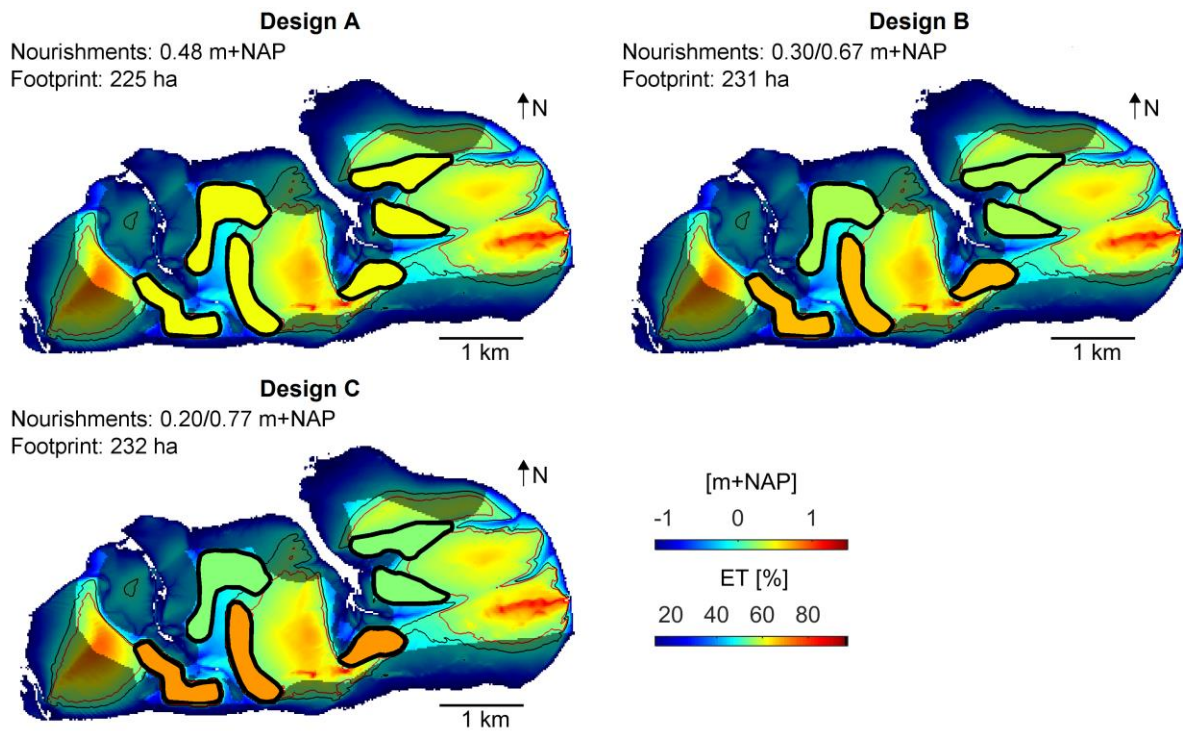
	Reference	Nourishment alternatives			Nourishment designs (Sand Relief)		
	No nourishment	Sand Ridge	Sand Relief	Sand Source	A	B	C
Nourishment characteristics							
Volume (M m ³)	n/a	1.3	1.3	1.3	1.3	1.3	1.3
# elements	n/a	2	10	1	6	6	6
Height [m NAP]	n/a	+0.55	+0.48	+1.70	+0.48	+0.30/+0.67	+0.20/+0.77
Area 50-80% exposure time (ha)							
Reference year (2010)	606	606	606	606	606	606	606
Pre-nourishment design (2013)	611	611	611	611	611	611	611
Post-nourishment design (2013)	611	741	752	631	755	749	755
Target year (2035)	421	607	612	442	607	619	624
Difference between target and reference year	-185	+1	+6	-164	+1	+13	+18
Other performance indicators							
Footprint (ha)	n/a	216	237	90	225	231	232
Circumference (km)	n/a	12	18	4	17	17	17
Relative scores							
Morphological aspect	n/a	0	+	-	++	++	+
Ecological aspect	n/a	0	+	-	+	++	++
Construction costs	n/a	+	0	++	+	+	+

443

444 4.3 Nourishment designs

445 The Sand Relief nourishment alternative was further optimized. The number of nourishment
 446 elements was decreased from 10 to 6 to reduce construction costs. Furthermore, the nourishment
 447 locations were adjusted to slow down the water drainage and sediment transport from the tidal flat
 448 and to even further reduce the potential risk of sediment coverage on the mussel beds. The resulting
 449 Designs A, B and C only vary in nourishment height (Figure 8). The higher southern nourishment
 450 elements are intended to shelter the lower northern elements by wave damping, and the height
 451 diversity could also provide additional ecological diversity and benefits. Differences in exposure time

452 can lead to a larger differentiation in benthic community structure, and higher nourishment
 453 elements make them faster accessible for wading birds during low tide, and could serve as a hub
 454 from which the birds can start to forage on the lower parts.
 455

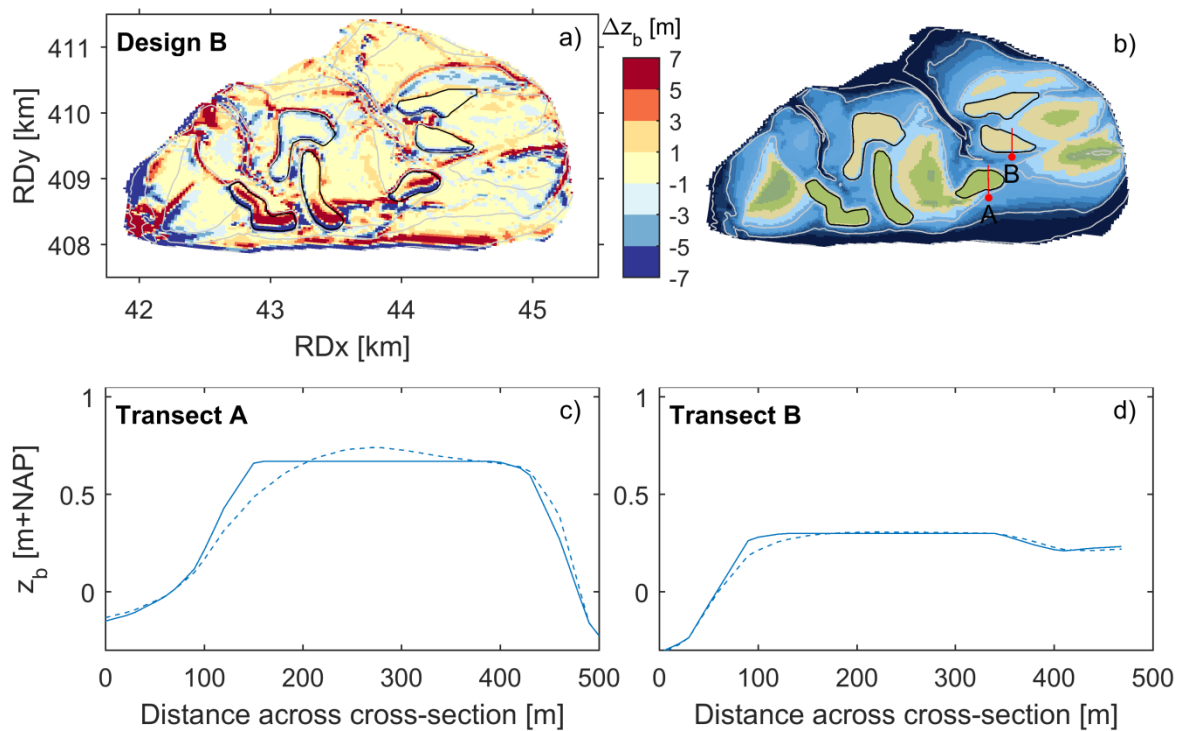


456
 457 *Figure 8. The nourishment Designs A, B and C on top of the 2013 bathymetry with 50% exposure time contour*
 458 *lines (black) plus the expected 20 cm relative erosion between 2013-2035 (red). The shaded regions are*
 459 *excluded from nourishing based on the suitability map (see Figure 4).*

460
 461 **4.4 Morphodynamic impact nourishment designs**

462 Figure 9 shows the computed bed level changes during a 1-year period for nourishment Design B.
 463 The figure shows that the nourishment elements mainly have a local impact and that bed level
 464 changes of the nourishment are of the same order of magnitude as the no-nourished Roggenplaat
 465 (Figure 5). The southern nourishment edges erode, whereas the northern edges accrete. This implies
 466 a migration in northern direction, in line with historically-observed bed level changes (Figure 3) and
 467 the dominant net transport direction (Figure 5). The northward transport of eroded sand also causes
 468 the nourishments to change shape and heighten locally. The southern nourishment elements are

469 exposed to the dominant southwesterly wind and wave direction and thus more dynamic than the
 470 more sheltered northern elements. This effect is strongest for the nourishment designs with higher
 471 southern elements, i.e. Design B and especially Design C. Therefore, it is expected that the higher
 472 southern elements will erode faster than the lower northern nourishments elements, and that this
 473 effect will be strongest for Design C.
 474



475
 476 *Figure 9. A: Computed bed level changes of nourishment Design B during a 1-year period. Red colors indicate*
 477 *accretion, and blue colors erosion. Only values on the Roggenplaat values are shown for clarity reasons. The*
 478 *black lines indicate the contours of the nourishment elements. B: location of transects A and B on top of the*
 479 *nourishment Design B bathymetry. C: morphological development of Transect A, D: morphological*
 480 *development of Transect B.*

481
 482 **4.5 Evaluation nourishment designs**

483 Table 1 shows the characteristics and performance indicators of the nourishment designs. The
 484 estimated nourishment costs did not differ between the designs. Designs B and C both provide more
 485 variety in height which can have a positive effect on biodiversity compared to Design A. The

486 expected erosion reduction of the northern nourishment elements in Design B and Design C
487 compared to Design A is beneficial, while the southern nourishment elements are expected to erode
488 faster. In case of the expected 0.2 m relative erosion, the (low) northern nourishments of Design C
489 are in 2035 just high enough to contribute to the 50-80% exposure time area, making this not a very
490 robust design. Therefore, Design B is preferred for the sand nourishment at the Roggenplaat.

491

492 **5. Discussion**

493 We developed an integral approach for designing nourishments on intertidal flats. The novelty of the
494 nourishment design process is threefold. First, we followed a structured work flow with explicit steps
495 to go from the objective to the preferred design. Second, system understanding based on a
496 combination of monitoring data, numerical modelling and expert judgement played a crucial role.
497 Third, we evaluated the nourishment designs on a range of criteria, combining economical,
498 ecological, morphological and technical considerations.

499

500 We studied the impact of nourishment designs on the short-term Roggenplaat morphodynamics
501 with a process-based Delft3D model with a grid resolution of 30 m. This resolution is too coarse to
502 resolve local features such as small tidal creeks and other bed level undulations. However, we
503 believe that the main mechanisms controlling the Roggenplaat morphodynamics are captured,
504 illustrated by the good reproduction of measured current velocities and wave heights on the shoal
505 (De Vet et al., 2018) and the qualitative agreement with bedform migration and net sand transport
506 direction, known from morphological data. Long-term (years) Delft3D morphological simulations
507 require long computation times and model results are inherently uncertain. Therefore, we estimated
508 the long-term intertidal area development using a simplified approach, assuming a uniform loss of
509 intertidal area due to the combined effect of SLR and erosion. This approach is supported by
510 historical data, and the short-term process-based model simulations. In this way we were able to

511 properly evaluate the long-term morphological impact of the nourishment alternatives in order to
512 choose the preferred design.

513

514 The Roggenplaat nourishment mainly has a conservation goal to preserve sufficient foraging grounds
515 for birds that feed during low tide on benthic macrofauna. As there is limited experience with such
516 measures, several uncertainties still exist with respect to the ecological development. Exposure time
517 is one of the critical elements that determines the suitability of an intertidal flat as foraging ground
518 for wading birds, besides food availability, sediment composition and behavior of the bird species
519 themselves. The foreseen Roggenplaat nourishment targets the areas with an exposure time of 50-
520 80%, aiming at preserving it until 2035. This is based on the historical development and current sea
521 level rise scenarios, but changes in these might result in changes in the erosive trend. When erosion
522 appears more rapidly, extra nourishments might be needed over time.

523

524 Although benthic animals live in sediment and crawl through it, they are sensitive to extreme burial
525 events as occur during sediment nourishments (Speybroeck et al., 2006; Van der Werf et al., 2015).
526 As a result, sediment nourishments will initially create large areas void of any living benthos. This is
527 from an ecological perspective a highly undesirable situation for two important reasons. Firstly, for a
528 certain period after the nourishment, the area has lost its function as feeding area for birds
529 (Peterson et al., 2006), which will persist till the benthic community has recovered (up to 3 years in
530 the Galgeplaat pilot nourishment, Van der Werf et al., 2015). This implies that a nourishment cannot
531 be carried out over the whole surface of a tidal flat without impacting the bird community. In case of
532 the Roggenplaat, the nourishment footprint (230 ha) is ~40% of the current 50-80% exposure area
533 and ~15% of the total Roggenplaat intertidal area. In this way a large part of the Roggenplaat is kept
534 intact for bird feeding while the nourished area is recovering over time. Secondly, the recovering
535 benthic community might differ from the original community present, because of changes in
536 exposure time and sediment composition (see also Van der Werf et al., 2015). This might change the

537 food availability for birds, which in turn could lead to changes in numbers of certain bird species
538 (positive as well as negative). In addition, creating large areas void of any living benthos typically
539 offers opportunities to invasive species to expand their habitat. For example, at the Oesterdam sand
540 nourishment high densities of the invasive manila clam *Ruditapes philippinarum* were observed a
541 year after the nourishment (Boersema et al., 2018). The latter has also been clearly shown for hard
542 engineering constructions in coastal waters, which can act as stepping stones facilitating invasions
543 (Airoldi et al., 2005; Bulleri & Airoldi, 2005). For both reasons, it is desirable to develop methods that
544 minimize the period during which the nourishment is without benthic life.

545

546 The concept of priming which we define as “giving an ecological imprint to an area void of a living
547 benthic community due to human interventions” may offer an opportunity to minimize the risk of
548 invading species to come in, community composition to shift and reduce the down-time as feeding
549 habitat. The concept entails that the benthos-rich 30 cm high top-layer of the original tidal flat is
550 removed before being nourished, and moved on top of the nourishment. In practice, this requires
551 highly-organized working schemes. This may for example be envisioned by applying the sand
552 nourishment as a series of bands. This approach will allow a band to be first covered with
553 “nourishment sand”, where after this band can be finished by adding a benthos-rich priming-layer.
554 This priming-layer can be obtained by removing the benthos-rich 30 cm top-layer from the band
555 directly adjacent to the nourished band, and which is the band that will be nourished next. To our
556 knowledge, this priming approach has not yet been tested on a field-scale. Therefore, it is proposed
557 to carry out a large experimental scale priming to test if we can accelerate and steer the
558 development of a benthic community by priming.

559

560 More general, we emphasize the need to monitor the Roggenplaat nourishment in detail. This
561 should include the hydrodynamics, the morphological development and the ecological development
562 (benthos and birds). The monitoring should also target the mussel culture plots, as to demonstrate

563 that the nourishment does not harm mussel production. The monitoring should ideally last for a
564 period of at least 5-10 years during which the main developments are expected to take place. This
565 will create a very useful database in order to assess to what extent the Roggenplaat nourishment
566 meets its objective. More general, the data can be used to increase and improve our understanding
567 and modelling of intertidal shoal morphology and ecosystem recovery dynamics. It is planned for to
568 carry out such a monitoring program.

569

570 **6. Conclusions**

571 We have developed an integral approach for designing intertidal shoal nourishments, and
572 demonstrated it for the design of the nourishment of the Roggenplaat intertidal shoal. It consists of
573 the following steps:

- 574 1. Characterization of the Roggenplaat morphology and ecology based on existing knowledge
575 and new monitoring data.
- 576 2. Translation of the main nourishment objective into an evaluation framework. The intertidal
577 area with 50-80% exposure is the key indicator for the foraging function. The nourishment
578 footprint and circumference are indicators of initial ecological disturbance and ecological
579 recovery time-scale, respectively.
- 580 3. Construction of a suitability map indicating potential nourishment areas, based on
581 morphological, ecological, economical and technical considerations.
- 582 4. Generation of nourishment alternatives and designs.
- 583 5. Calculation of the nourishment impact on short-term hydro-morphodynamics using a
584 Delft3D numerical model.
- 585 6. Prediction of long-term future shoal development using a simplified approach.
- 586 7. Integral evaluation of the nourishment alternatives leading to the preferred design using the
587 evaluation framework. This includes an expert judgement of the morphological and
588 ecological aspects, and an estimation of the construction costs.

589

590 The final nourishment design consists of 6 nourishment elements. The nourishment height is such
591 that the intertidal area with 50-80% exposure time is directly above the target value and is designed
592 to stay so until 2035. The higher southern nourishment elements are intended to shelter the lower
593 northern elements by wave damping, and the height diversity also provides ecological diversity.

594

595 **7. Lessons learned from design process**

596 The integrated approach enabled us to make a design that is expected to fulfill the Roggenplaat
597 nourishment objective, accounting for ecological, morphological, economical and technical aspects.
598 This integrated approach could form a basis for other intertidal shoal nourishment designs. In
599 particular, we learned the following generic lessons:

- 600 • System understanding at the right scale is essential to make a good nourishment design.
601 Ideally, system understanding is based on a combination of monitoring data, numerical
602 modelling and expert judgement.
- 603 • A combination of a detailed, process-based short-term numerical modelling and a simplified
604 data-driven approach to estimate the long-term intertidal area evolution enabled the
605 evaluation of the morphological aspects of the nourishment designs.
- 606 • Translation of the objective in quantifiable indicators allows transparent and objective
607 evaluation of the nourishment design. Furthermore, it guides the cooperation between
608 multidisciplinary researchers and serves as a means of communication with stakeholders.
- 609 • Expert judgment is an important unavoidable element in the evaluation framework, as long-
610 term predictions of morphological and ecological developments remain uncertain.
- 611 • A nourishment suitability map avoids unrealistic nourishment areas, limits the solution
612 space, and is a powerful stakeholder communication tool.

613

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621

622 **Author contributions**

623 J.J. van der Werf coordinated the research and was main author of Sections 1, 3.1, 4.1, 4.3, 5, 6 and
624 7. P.L.M. de Vet wrote Section 2 (morphology) and Section 3.5. M.P Boersema wrote Section 3.3. T.J.
625 Bouma wrote the paragraph on priming in the discussion (Section 5), based on research by L.M.
626 Soissons. A.J. Nolte wrote Section 3.2. R.A. Schrijvershof wrote Sections 3.4 and 4.4. J. Stronkhorst
627 wrote Sections 4.2 and 4.5. E. van Zanten initiated this study and played an indispensable role in the
628 nourishment design process. T. Ysebaert wrote Section 2 (ecology). All authors contributed to the
629 introduction, discussion and conclusions.

630

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