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van der Werf, J. J.; de Vet, P. L.M.; Boersema, M. P.; Bouma, T. J.; Nolte, A. J.; Schrijvershof, R. A.; Soissons, L. M.; Stronkhorst, J.; van Zanten, E.; Ysebaert, T.

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1   **An integral approach to design the Roggenplaat intertidal shoal nourishment**

2   *J.J van der Werf[1,2], P.L.M. de Vet[1,3], M.P. Boersema[4,5], T.J. Bouma[4,6,7], A.J. Nolte[1], R.A. Schrijvershof[1],*

3   *L.M. Soissons[6], J. Stronkhorst[1,4], E. van Zanten[5], T. Ysebaert[6,8]*

4   [1] Deltares, Delft, The Netherlands

5   [2] University of Twente, Enschede, The Netherlands

6   [3] Delft University of Technology, Delft, The Netherlands

       [4] HZ University of Applied Sciences, Vlissingen, The Netherlands

       [5] Rijkswaterstaat, Ministry of Infrastructure and Water Management, The Netherlands

7   [6] Department of Estuarine and Delta Systems. Royal Netherlands Institute of Sea Research (NIOZ) and Utrecht

8   University, Yerseke, The Netherlands

9   [7] Faculty of Geosciences, Department of Physical Geography, Utrecht University, The Netherlands.

10   [8] Wageningen Marine Research, Wageningen University and Research, Yerseke, The Netherlands

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14

15   **Abstract**

16   The Eastern Scheldt, a tidal basin in the southwest of The Netherlands, underwent large physical and

17   ecological changes due to a system-wide human interference. The construction of a storm surge

18   barrier at the seaward side and closure of the upstream branches in the 1980s resulted in intertidal

19   flat erosion. This has far reaching consequences for the ecological functioning of these habitats,

20   especially as foraging ground for many wader species. Therefore, a 1.3 million m^3 sand nourishment

21   is foreseen on the Roggenplaat intertidal shoal to mitigate the erosion and preserve suitable

22   foraging habitat for waders for the coming 25 years. This paper presents an integral nourishment

23   design approach. It consists of the following steps: (i) understanding the morphology and ecology, (ii)

24   translation of the nourishment objective into an evaluation framework, (iii) construction of a

25   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.

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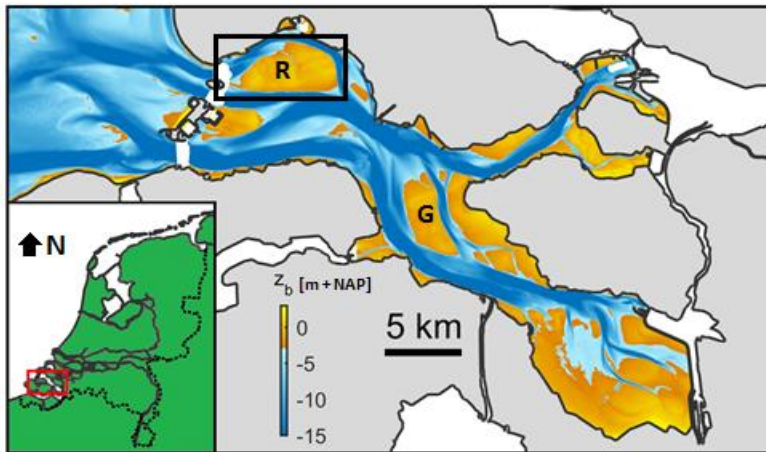
73

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 Paree, 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 m^3 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   (Vonhögen-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.

2. Translation of the main nourishment objective into an evaluation framework.

3. Construction of a suitability map indicating potential nourishment areas, based on morphological, ecological, economical and technical considerations.

4. Generation of nourishment alternatives and designs.

5. Calculation of the nourishment impact on short-term hydro-morphodynamics using a Delft3D numerical model.

6. Prediction of the long-term future shoal development using a simplified approach.

7. Integral evaluation of the nourishment alternatives leading to the preferred design.

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

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

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

6

139 NAP[1]-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 > NAP+1.02 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
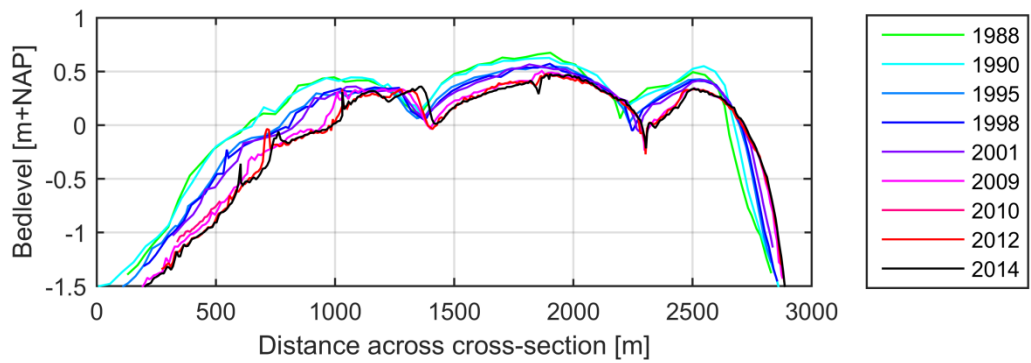
149 also Figure 3.

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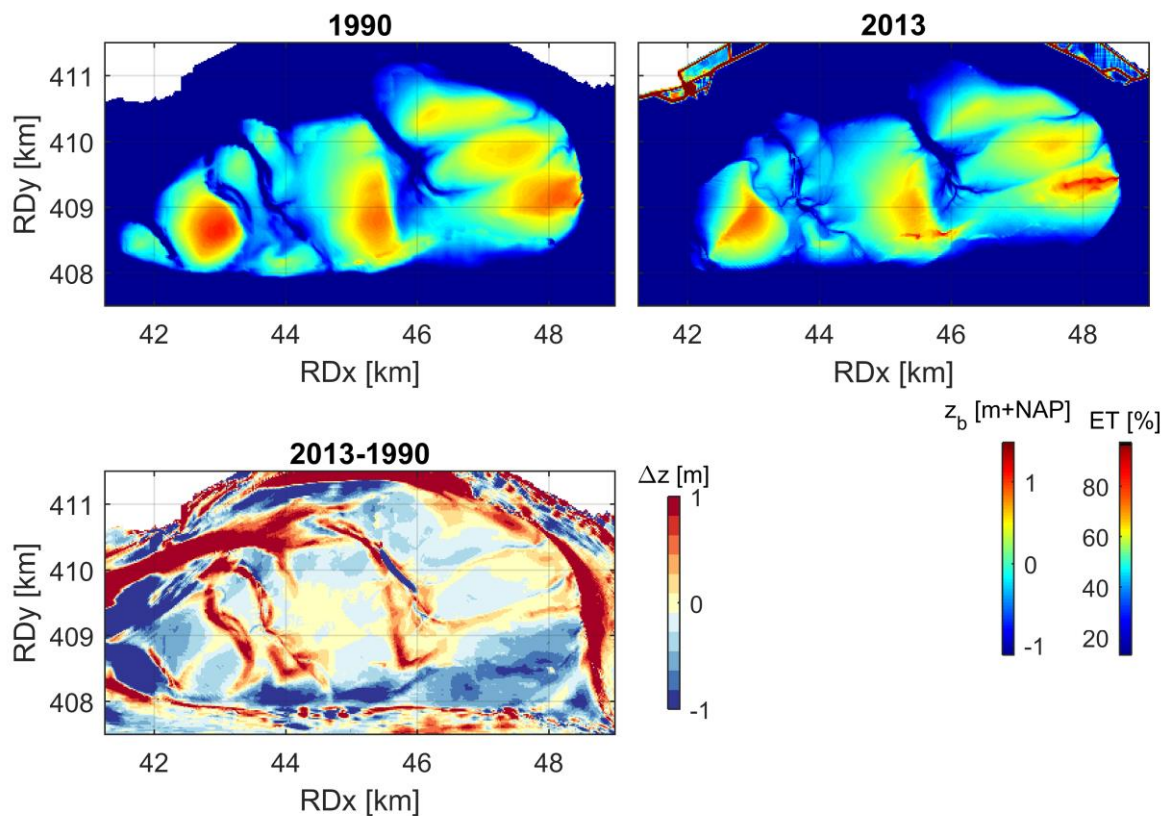
152   *Figure 2. Top: bathymetry maps of the Roggenplaat for the years 1990 and 2013. Both the color scale in meters*

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 ± 3 µm (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

165   µm), 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 ± 615 ind.m^{-2}, the average

173   biomass 31 ± 4 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 m^3 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 is 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

11

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 (Walles 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.

13

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

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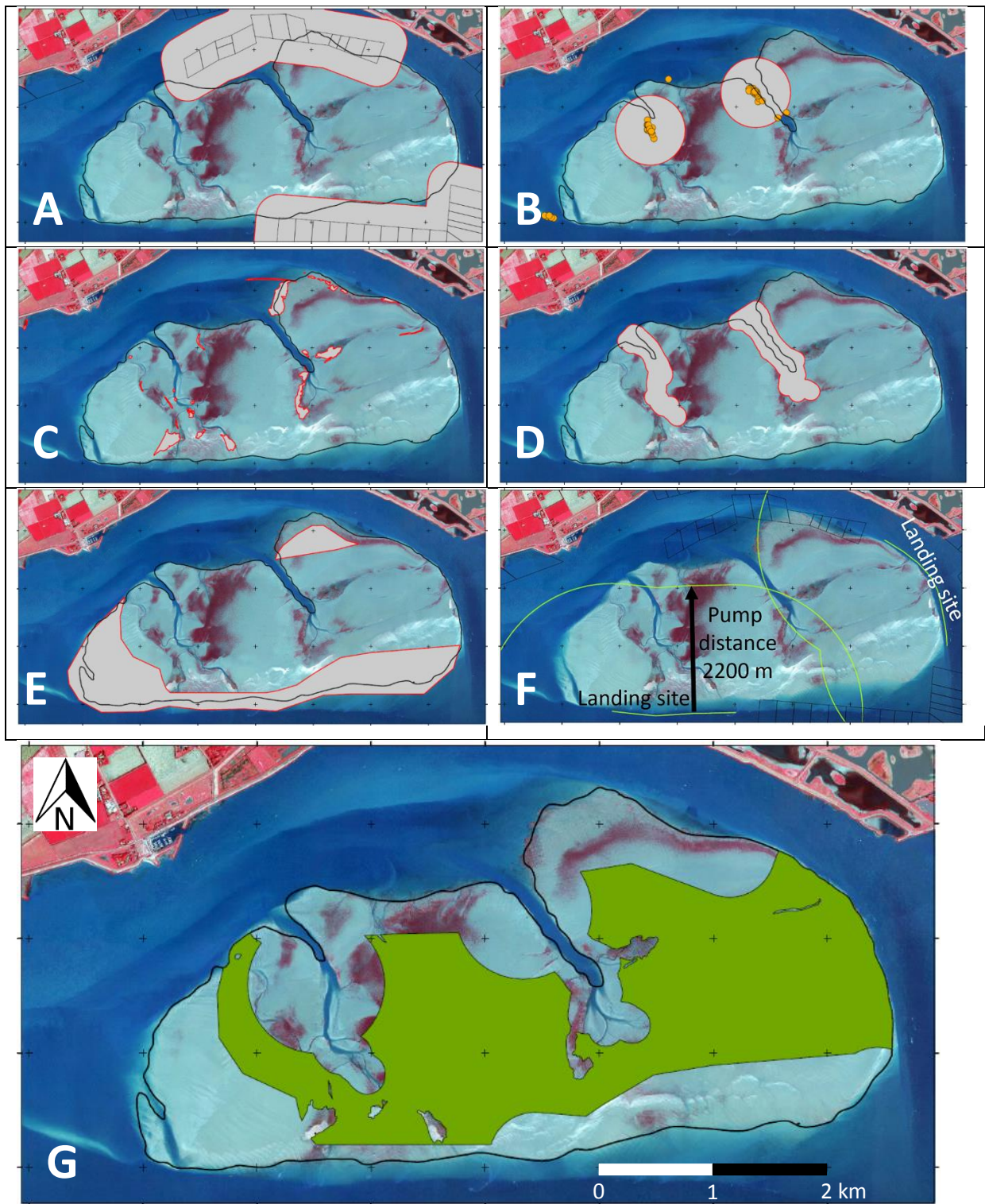
Figure 4. A-G: Roggenplaat areas excluded as potential nourishment areas. A: 400 m away from commercial mussel beds (grey lines). B: 600 m away from the two main seals resting areas (orange dots: observed seals). C: oyster reefs. D: 150 m away from the two main tidal creeks. E: highly erosive areas.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

15

318

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.

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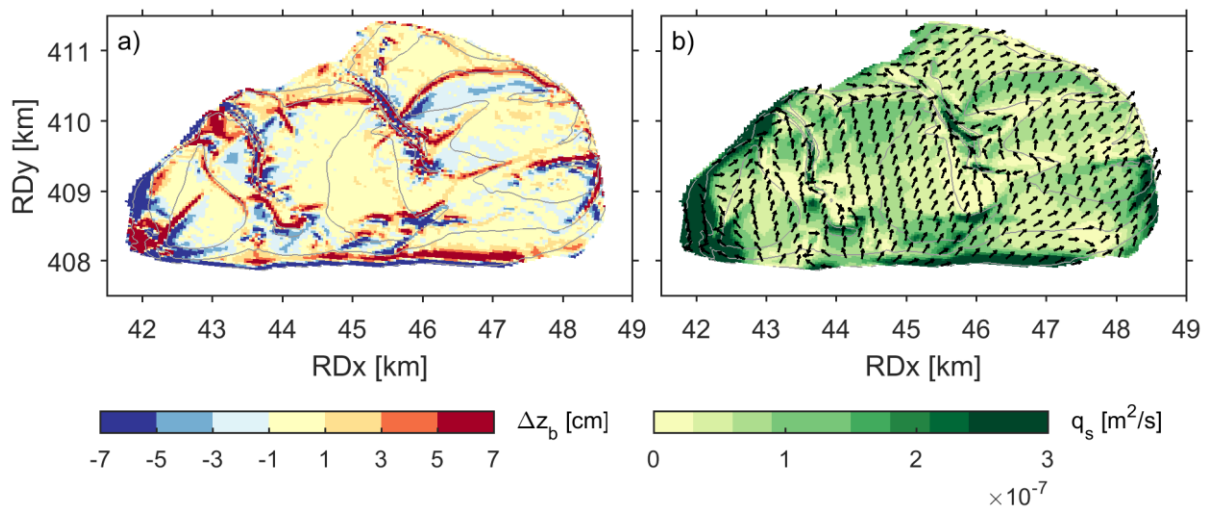
Figure 5. Computed bed level changes (a) and net sand transport rates (b) on the no-nourished Roggenplaat during 1 year based on the May 2015 forcing and a morphological factor of 12. Only values above MLW (mean low water) are shown for clarity reasons. Red colors in (a) indicate accretion, blue colors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

3.5 Simplified approach to predict future loss of intertidal area

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

Therefore, we investigated the evolution of the 50-80% exposure time area using a simplified approach. The main assumptions are that i) the average lowering rate of the Roggenplaat is spatially uniform, ii) the relative (with respect to mean sea level) erosion of the Roggenplaat is due to a constant SLR and bed level erosion rate, iii) the bed level erosion rate is not affected by the nourishment. The first assumption is supported by the evolution of the Roggenplaat hypsometry between 1990 and 2013 (see De Vet et al., 2017). The Delft3D model results showed that the 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
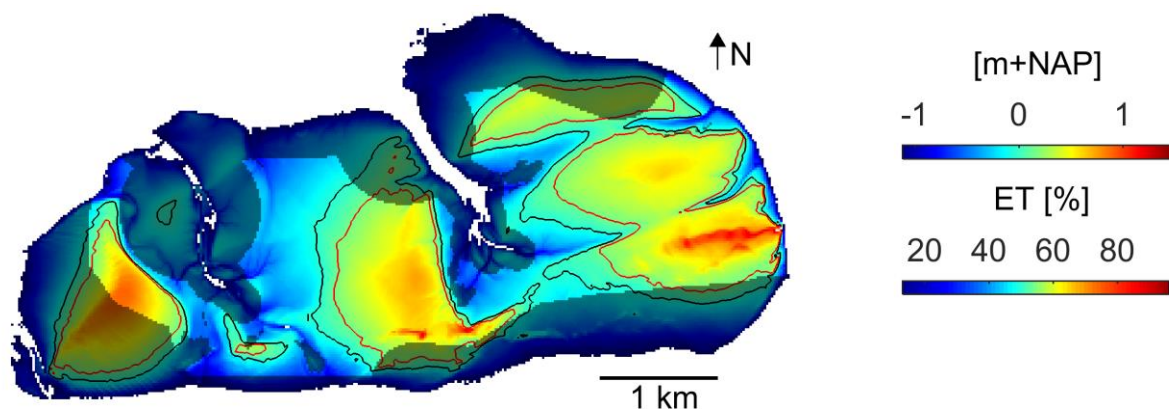
379

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　*suitabiliy 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

400
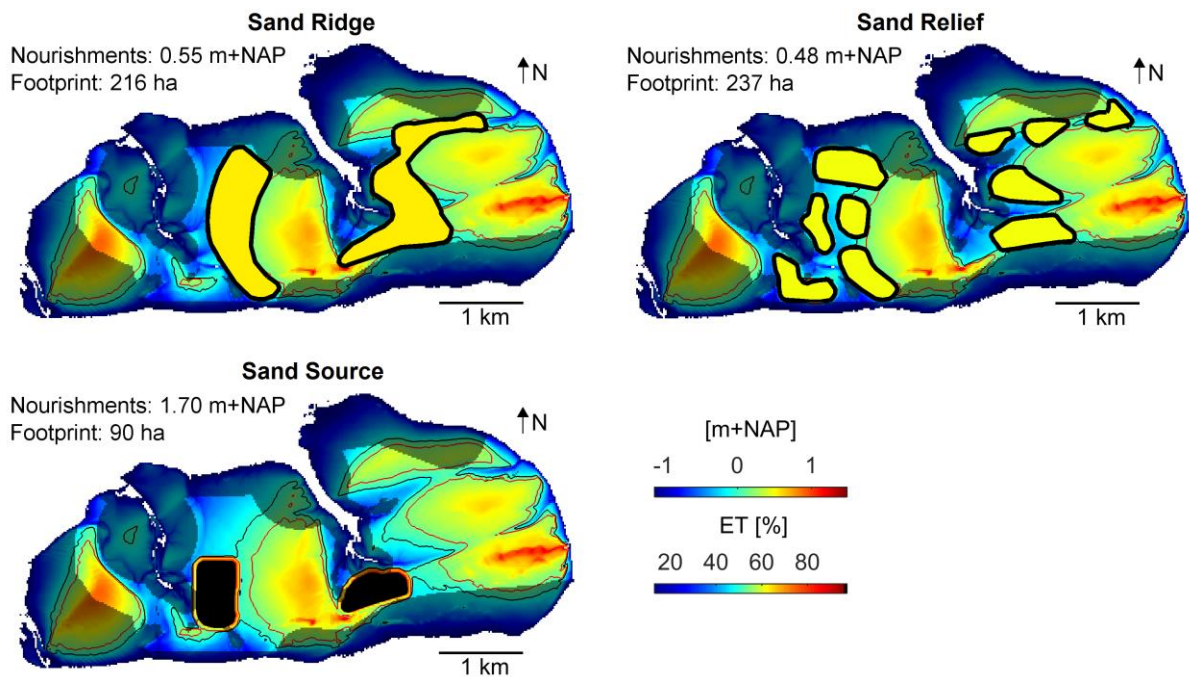
Figure 7. The nourishment alternatives Sand Ridge, Sand Relief and Sand Source on top of the 2013 bathymetry

with 50% exposure time contour lines (black) plus the expected 20 cm relative erosion between 2013-2035 (red).

The shaded regions are excluded from nourishing based on the suitabiliy map (see Figure 4). The Sand Source

nourishmen has a black colourm because its height is off scale.

4.2 Evaluation alternatives

Table 1 shows the characteristics and performance indicators (based on the evaluation framework

described in Section 3.2) of the nourishment alternatives, as well as of the no-nourishment

reference scenario. The key indicator is the intertidal area with a 50-80% exposure time in 2035. If

this number is smaller than the 2010 value, the nourishment design is rejected. The other two

indicators are the nourishment footprint (smaller footprint is considered positive, because of

potentially faster ecological recovery) and the nourishment circumference (longer circumference is

considered positive, because it means more feeding hotspots for wading birds). These three

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

Table 1. Characteristics, performance indicators and scores of the Roggenplaat shoal nourishment alternatives

and designs, and of the reference, i.e. no-nourishment scenario. The key performance indicator, the area with

50-80% exposure time, was estimated using a simple modelling approach. The scores on the morphological

aspect were based on this key indicator and on expert judgment using Delft3D numerical model simulations,

amongst other things. The ecological scores followed from an expert judgement based on the area with 50-80%

exposure time, the nourishment footprint, the nourishment circumference, and other considerations. The

*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 indictors							
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

4.3 Nourishment designs

The Sand Relief nourishment alternative was further optimized. The number of nourishment

elements was decreased from 10 to 6 to reduce construction costs. Furthermore, the nourishment

locations were adjusted to slow down the water drainage and sediment transport from the tidal flat

and to even further reduce the potential risk of sediment coverage on the mussel beds. The resulting

Designs A, B and C only vary in nourishment height (Figure 8). The higher southern nourishment

elements are intended to shelter the lower northern elements by wave damping, and the height

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
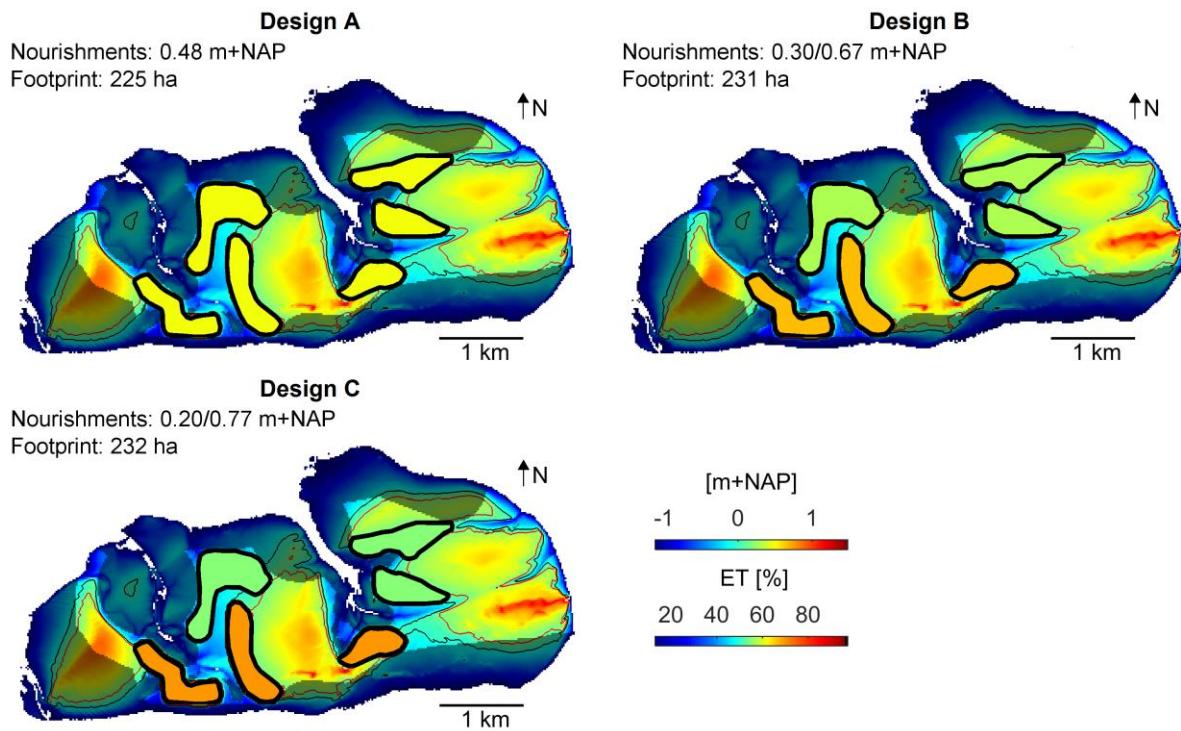
Figure 8. The nourishment Designs A, B and C on top of the 2013 bathymetry with 50% exposure time contour

lines (black) plus the expected 20 cm relative erosion between 2013-2035 (red). The shaded regions are

excluded from nourishing based on the suitability map (see Figure 4).

460

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 sourthern nourishment elements are

23

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   sourthern 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
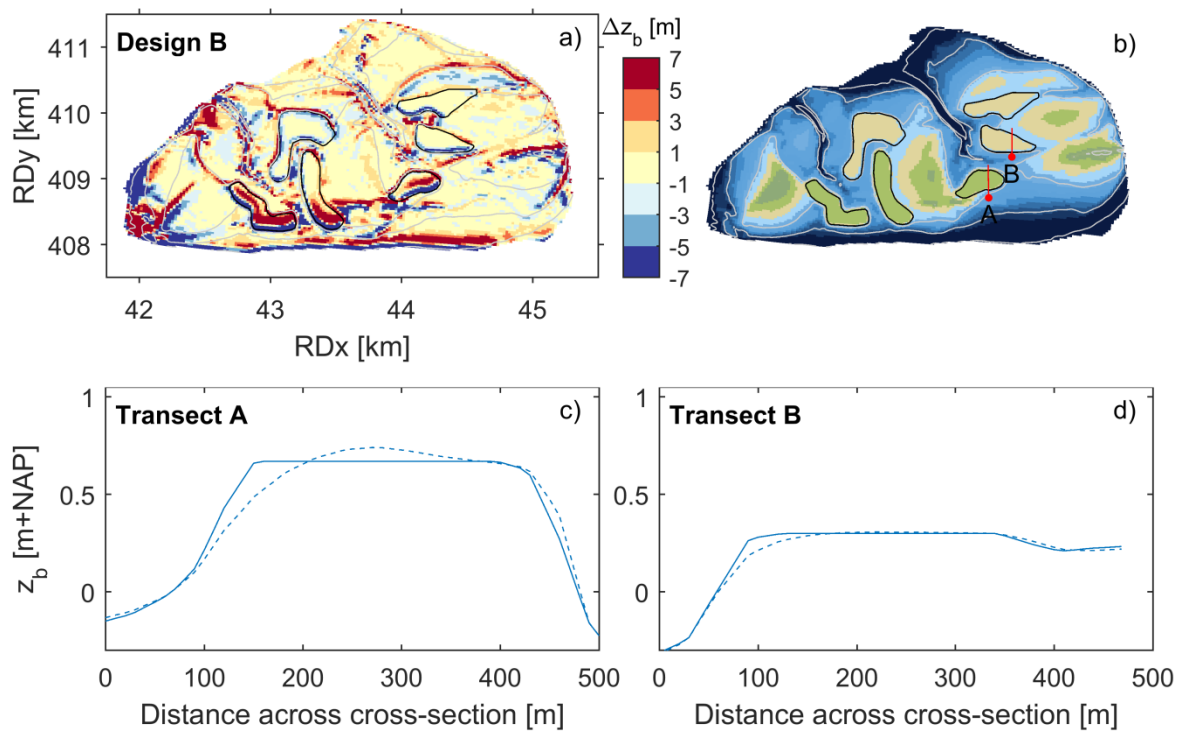
475

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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