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Unravelling interactions between salt marsh evolution and sedimentary processes in the Wadden Sea (south-eastern North Sea)

Abstract:	Salt marshes in the Wadden Sea constitute about 20% of all salt marshes along European coasts. They are of immense importance for coastal protection reasons and as habitat for coastal plant, bird, and invertebrate species. The Wadden Sea is a coastal sedimentary ecosystem in the south-eastern North Sea. Besides salt marshes, it is composed of tidal flats, high sands, and sandy shoals, dissected by (sub)tidal channels and located behind barrier islands. Accelerated global sea-level rise (SLR) and changes in storm climate have been identified as possible threats for the persistence of the Wadden Sea ecosystem including its salt marshes. Moreover, it is known that the amount and composition of the sediment available for salt marshes are the most important parameters influencing their ability to adapt to current and future SLR. Assessing these parameters requires a thorough understanding of the sedimentary system of the salt marshes and the adjacent tidal basins. In the present review, we investigate and unravel the interactions of sedimentary processes in the Wadden Sea with the processes taking place on salt marshes. We identify the most crucial processes and interactions influencing the morphological development of salt marshes in the Wadden Sea. A conceptual model is proposed, intended as a framework for improved understanding of salt marsh development and for incorporation into new salt marsh models. The proposed model may also be applicable to regions other than the Wadden Sea.

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Review Article

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3

4   **Abstract**

5

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7   coasts. They are of immense importance for coastal protection reasons and as habitat for

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9   ecosystem in the south-eastern North Sea. Besides salt marshes, it is composed of tidal flats,

10   high sands, and sandy shoals, dissected by (sub)tidal channels and located behind barrier

11   islands. Accelerated global sea-level rise (SLR) and changes in storm climate have been

12   identified as possible threats for the persistence of the Wadden Sea ecosystem including its

13   salt marshes. Moreover, it is known that the amount and composition of the sediment

14   available for salt marshes are the most important parameters influencing their ability to adapt

15   to current and future SLR. Assessing these parameters requires a thorough understanding of

16   the sedimentary system of the salt marshes and the adjacent tidal basins. In the present

17   review, we investigate and unravel the interactions of sedimentary processes in the Wadden

18   Sea with the processes taking place on salt marshes. We identify the most crucial processes

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20   Sea. A conceptual model is proposed, intended as a framework for improved understanding of

21   salt marsh development and for incorporation into new salt marsh models. The proposed

22   model may also be applicable to regions other than the Wadden Sea.

23

24   **Keywords**

25

26   Salt marshes, Wadden Sea, sea level rise, sediment dynamics, tidal flats, modelling

27

28   **I   Introduction**

29

30   The Wadden Sea ecosystem stretches over 450 km along the coast of The Netherlands,

31   Germany, and Denmark and is characterized by a semidiurnal tidal regime (Fig. 1) (CWSS,

32   2008). It is regarded as one of the world's largest unbroken wetland systems, consisting of

33   barrier islands, sandy shoals, tidal sand and mud flats, (sub)tidal channels, and coastal salt

34   marshes. The salt marshes are located at the interface between the tidal flats and the upland

35   and cover a total area of about 400 km^2. Nearly 50% of them are foreland marshes, in most

36   cases artificially created by the implementation of brushwood groynes in the tidal flats, and

37   located in front of the dikes along the mainland coast (Esselink et al., 2009). In contrast, most

38   natural salt marshes are found at the leeward side of the barrier islands (back-barrier marshes)

39   (Bakker et al., 2005).

40   Salt marshes in the Wadden Sea are considered important for coastal protection (Möller, 2006;

41   Möller et al., 1999) and as habitat for coastal birds, invertebrates, and specialized plant species

42　(Niedringhaus et al., 2008; van der Maarel and van der Maarel-Versluys, 1996). In addition, salt

43　marshes have an important filter function with regard to nutrients and pollutants (e.g. heavy

44　metals) (Reise et al., 2010) and act as a sink for fine-grained sediments (Andersen and Pejrup,

45　2001; Pejrup et al., 1997).

46　Growth and survival of salt marshes are primarily controlled by hydromorphological

47　parameters such as inundation frequency and sediment availability (Pethick, 1981; van Wijnen

48　and Bakker, 2001) as well as the influence of vegetation on the sedimentation process itself

49　(Fagherazzi et al., 2012). Therefore, salt marshes are highly susceptible to changes of the

50　hydromorphological regime, triggered, for example, by a rising sea level and/or increased

51　storm activity (Morris et al., 2002; Mudd et al., 2004; Reed, 1995). Various modelling studies

52　have shown that salt marshes may be able to accrete with roughly the same rate as sea level

53　rises, if sediment availability is sufficient (French, 1993; D'Alpaos et al., 2011; Kirwan et al.,

54　2010). However, as a consequence of recent climate change (including sea level rise (SLR)) and

55　various anthropogenic pressures, salt marshes have been lost and/or are expected to be lost in

56　the future due to drowning and/or lateral erosion in many parts of the world (Duarte et al.,

57　2008; McFadden et al., 2007; Nicholls et al., 1999). In contrast to this global trend, salt marsh

58　areas in the Wadden Sea have remained stable or have been expanding since the end of

59　embanking about 25 years ago (Esselink et al., 2009; Wolff et al., 2010; Stock, 1998). Partly,

60　this trend is due to the artificial creation of foreland marshes (Esselink et al., 2009). For the 21st

61　century and beyond, accelerated SLR has been identified as a major threat for the salt marshes

62　in the Wadden Sea, since not enough sediment may be available for their vertical growth (e.g.

63   Andersen et al., 2011; van Wijnen and Bakker, 2001) and since artificial salt marsh creation is

64   reduced for nature protection reasons (Esselink et al., 2009).

65   For the future ability of the Wadden Sea salt marshes to adapt to SLR, it is assumed that the

66   local availability of fine-grained sediments is the most important variable (Andersen et al.,

67   2011; Schuerch et al., 2013). This implies that understanding the import of fine-grained

68   sediments into the tidal basins as well as the sediment transport processes on the tidal flats

69   and the salt marshes is crucial for estimating the future development of these marshes.

70   However, the interactions between the sedimentary processes of the tidal basins, tidal flats,

71   and salt marshes are insufficiently studied and have not yet been incorporated into predictions

72   for future salt marsh development.

73   With this review, we aim to identify knowledge gaps regarding the main processes that control

74   morphodynamics within the tidal basin – tidal flat – salt marsh continuum and suggest how

75   these gaps can be bridged in salt marsh modelling. For this purpose we have developed a

76   conceptual model that helps to improve the formulation of salt marsh models that predict the

77   ability of coastal salt marshes to adapt to future SLR. Rather than looking at salt marshes as an

78   isolated landscape feature, a more comprehensive and broader-scale approach is taken for

79   highlighting the role of salt marshes in the surrounding sedimentary system. The Wadden Sea

80   ecosystem, in this context, serves as a case study, since it can be considered representative of

81   many similar coastal systems around the world, and extensive research with respect to its

82   morphological functioning has been conducted (Wang et al., 2012).

83

84   **II   Methodology**

85

86   In the following sections, we outline the sedimentary processes and interactions relevant for

87   the morphological development of salt marshes in the Wadden Sea. Where possible, existing

88   process knowledge is reviewed based on studies directly referring to the Wadden Sea

89   ecosystem. However, for site-independent processes driving the Wadden Sea sedimentary

90   system, a more general review approach is taken referring to the most important literature in

91   the field.

92   We start with a synthesis of the processes governing the salt marsh itself and the identification

93   of knowledge gaps. We continue with a description of the existing and missing knowledge on

94   tidal flat dynamics and the processes taking place in the tidal basin. The importance of all these

95   processes for the morphological development of salt marshes in the Wadden Sea is thereby

96   highlighted. In the end, we integrate this knowledge in a conceptual model that will help salt

97   marsh modellers to expand their models and improve the model performance with respect to

98   short- and long-term temporal as well as spatial variations in salt marsh development.

99

100   **III Morphodynamics of coastal salt marshes**

101

102   *1   Vertical salt marsh development*

103

104   *a Processes of vertical salt marsh growth.* Driven by regular tidal to episodic wind induced

105   inundations, the growth of salt marshes is controlled by a continuous input of mainly mineral

106   (and much less organic) sediment brought onto the salt marsh by the flooding water. Such

107   allochthonous accretion is strongly related to the relative elevation of the salt marsh within

108   the tidal frame, the inundation frequency, and the amount of external sediment supplied by

109   the flooding water (Kirwan et al., 2010; French, 1993; van Wijnen and Bakker, 2001). Besides

110   the allochthonous accretion, salt marshes accrete as a result of autochthonous growth, the

111   accumulation of aboveground and belowground biomass including the growth of benthic

112   microflora (e.g. cyanobacteria and eucaryotic algae, such as diatoms and *Vaucheria*) (Chmura,

113   2013; Sullivan and Currin, 2002).

114   For allochthonous marsh accretion, vegetation acts as a facilitating ecosystem-engineer. It

115   reduces lateral and vertical marsh erosion and stabilizes the soil through rooting and other

116   modifications of the soil properties (Feagin et al., 2009; Howes et al., 2010). Moreover, the

117   aboveground plant structures reduce flow velocities and turbulence, enhancing the deposition

118   of mineral and organic sediment particles by trapping suspended sediments directly and by

119   increasing particle settling velocities in densely vegetated environments (Fig. 2) (Leonard and

120   Croft, 2006; Mudd et al., 2010; Nepf, 1999; Stumpf, 1983). Spatial variability in the

121   depositional pattern is introduced by the presence of vegetation as suspended sediment

122   concentrations of the flooding water are depleted while travelling over the vegetated marsh

123   surface (Christiansen et al., 2000; French and Spencer, 1993; Temmerman et al., 2003a).

124   Depending on the marsh elevation, different vegetation types and densities establish on the

125   marsh that vary with respect to their physical plant characteristics (e.g. stem diameter and

126   stiffness, leaf area, vertical biomass distribution) and their potential to reduce flow velocities

127   and turbulences as well as their ability of directly capturing sediments (Neumeier and Amos,

128   2006; Mudd et al., 2010; Marani et al., 2013). Additionally, sedimentation rates over vegetated

129   marsh surfaces vary spatially depending on the ratio of inundation height to vegetation height

130   (Temmerman et al., 2005) with smaller spatial variability, when the marsh vegetation is

131   completely submerged during an inundation event (Temmerman et al., 2005).

132   Marsh growth via vertical accretion is counteracted by autocompaction (Allen, 2000). This

133   process is generally assumed to be negligible on allochthonous marshes, but highly important

134   in autochthonous marshes (Cahoon et al., 1995; Allen, 2000). However, Bartholdy et al. (2010)

135   find autocompaction to be of major importance for a barrier-connected mineralogenic salt

136   marsh in the Danish Wadden Sea. Besides autocompaction, the salt marsh surface may also be

137   lowered by external factors, such as tectonic or human-induced soil subsidence (e.g. de Vlas,

138   2005).

139   If total marsh accretion exceeds the combined effect of soil subsidence, autocompaction, and

140   eustatic SLR, the marsh elevation increases relative to mean sea level (MSL). Inundation

141   frequency then decreases and sedimentation rates slow down when vegetation succession

142   proceeds from pioneer marsh over low marsh to high marsh vegetation (Adam, 1990;

143   Bockelmann et al., 2002; Leendertse et al., 1997; Olff et al., 1997).

144   *b Vertical salt marsh growth under the influence of SLR.* Salt marsh growth usually exists in a

145   quasi dynamic equilibrium with SLR (Allen, 1995; Allen, 2000; Morris et al., 2002). More

146   frequent and higher inundation events enhance mineral sedimentation when sea level rises. A

147   parallel increase of biomass is observed on the salt marsh up to a critical SLR rate (Morris et al.,

148   2002). Given sufficient sediment supply, most marshes are likely to survive SLR (Kirwan and

149   Temmerman, 2009). If sediment supply decreases, the salt marsh may not be able to grow fast

150   enough (Andersen et al., 2011), leading to regressive succession (Warren and Niering, 1993) or

151   drowning of the marsh (Fig. 3) (D'Alpaos et al., 2011; Kirwan et al., 2010). In the Danish

152   Wadden Sea, Andersen et al. (2011) found indications for a decreasing sediment supply, either

153   caused by a long-term regime shift or by short term variations in the sedimentary system of

154   the Wadden Sea. Also in other parts of the Wadden Sea, trends of regressive succession are

155   currently observed (Leendertse et al., 1997; Schröder et al., 2002; Stock, 2011), although this

156   may partly be attributed to grazing activities (Bakker, 1985; Stock, 2011; Nolte et al., 2013).

157   Apart from local sediment supply, the survival of salt marshes is crucially dependent on tidal

158   range (Fig. 3) (Harrison and Bloom, 1977; French, 1993; D'Alpaos et al., 2011; Kirwan et al.,

159   2010). In macro-tidal environments tidal currents are stronger, thereby enhancing sediment

160   resuspension in the tidal basin and on tidal flats in particular, resulting in a higher sediment

161   supply for the salt marsh (Temmerman et al., 2004a). Additionally, a large tidal range increases

162   the ability of salt marshes to cope with SLR by allowing the marsh to cover a wider elevational

163   range, thus surviving longer even if marsh elevation decreases relative to MSL (Kirwan and

164   Guntenspergen, 2010).

165   *c Vertical salt marsh growth and storm activity.* Apart from SLR and the prevailing tidal regime

166   the occurrence of strong onshore wind and storm events crucially affects marsh development

167   (Bartholdy et al., 2004; Schuerch et al., 2013). Positive effects of storm activity on vertical salt

168   marsh accretion rates are increased inundation frequencies and heights as well as increased

169   sediment supply (Stumpf, 1983; Bartholdy et al., 2004; Bellucci et al., 2007; Schuerch et al.,

170   2012). Sedimentation rates are generally assumed to gradually increase with higher inundation

171   depths, since sediment concentrations of the flooding water and the absolute amount of

172   sediment transported onto the marsh platform are higher (Temmerman et al., 2003b).

173   Nevertheless, it appears that largest sedimentation rates are associated with time periods in

174   which many strong wind or weak storm events occur, while the occurrence of extreme storm

175   events seems to be less important (Bartholdy et al., 2004). This may be explained simply by the

176   frequency of inundation events, but also by the high probability of inundations overtopping

177   the vegetation canopy. This is, in turn, associated with higher depth-averaged flow velocities, a

178   process, which has hardly been investigated, but is discussed in more detail later.

179   Consequently, sedimentation rates increase more slowly with increasing inundation height as

180   soon as the vegetation canopy is completely submerged during inundation (Schuerch et al.,

181   2012; Neumeier and Amos, 2006).

182   Generally, micro-tidal marshes have been shown to benefit more from increased storm activity

183   than macro-tidal marshes, since sediment dynamics in micro-tidal marshes are rather

184   controlled by wind induced processes than in macro-tidal marshes, which are more governed

185   by tidal currents (Stumpf, 1983; Kolker et al., 2009). Additionally, the effect of storm surges

186   with regard to inundation heights and frequencies as well as increased sediment supply tends

187 to be relatively more important in micro-tidal marshes than in macro-tidal marshes (Stumpf,

188 1983).

189

190 *2 Lateral marsh dynamics*

191

192 *a Physical drivers for lateral marsh erosion.* Besides vertical growth, salt marsh development is

193 subject to lateral marsh dynamics. Lateral salt marsh erosion and expansion are suggested to

194 be part of a cyclic behaviour, where an erosive phase of salt marsh retreat is followed or

195 accompanied by the re-establishment of pioneer vegetation in front of the marsh platform

196 (Yapp et al., 1917; Redfield, 1972; Esselink et al., 2009; van de Koppel et al., 2005; Singh

197 Chauhan, 2009). Salt marshes may emerge at upper tidal flats when and where sediment

198 accretion outpaces SLR with inundation frequency and bottom shear stress gradually

199 decreasing. The developing vegetation stabilizes the sediment and further enhances sediment

200 accretion (Fig. 2) (Orson et al, 1985; van de Koppel et al., 2005). In case sediment supply is not

201 sufficient for the tidal flat to adapt to SLR (e.g. due to decreased sediment availability or

202 increased SLR), the tidal flat in front of the salt marsh is lagging behind the accretion rate on

203 the salt marsh platform (Fagherazzi et al., 2006). A steepening scarp develops at the edge of

204 the salt marsh, prone to wave attacks, and salt marsh retreat by lateral erosion is initiated (Fig.

205 5) (Mariotti and Fagherazzi, 2010). This process may lead to catastrophic collapse of an entire

206 salt marsh (Mariotti and Fagherazzi, 2013). Callaghan et al. (2010) showed that gently sloping

207 and highly elevated tidal flats with high sediment stability most effectively attenuate wave

208   energy, even at highly exposed sites, and thereby inhibit lateral erosion of salt marshes

209   (Callaghan et al., 2010). Locally, this can also result in a reduced sediment supply for the

210   vertical growth of the salt marsh (Reed, 1988; van Leeuwen, 2008).

211   Besides the morphology of the tidal flats, wave impacts on seaward marsh edges and on the

212   adjacent tidal flats are influenced by local hydrodynamics. Strong wind or storm events

213   producing waves within tidal basins may coincide with high tide, when the tidal flats are

214   completely inundated. In such a case, larger fetch lengths, wave heights, and wave periods

215   increase the probability of vertical erosion of higher elevated tidal flats (Fagherazzi and

216   Wiberg, 2009). Elevated water levels may also amplify marsh edge erosion, since incoming

217   waves could directly reach to the scarp of the salt marsh (Tonelli et al., 2010).

218   *b Lateral marsh erosion in the Wadden Sea.* The process of lateral salt marsh erosion is of great

219   importance in the Wadden Sea. Successive embankments have reduced salt marsh area by

220   about 90% over the last millennium and often have shifted the coastline seaward (Reise,

221   2005). As a consequence, tidal basins became truncated at the landward side and the loss of

222   area increased the hydrodynamic energy due to an increased tidal range and enhanced storm

223   tide wedge (Wang et al., 1995; Flemming and Nyandwi, 1994; Reise, 2005). Lateral erosion at

224   the seaward edges of the foreland marshes was initiated (Reise et al., 2003). Brushwood

225   groynes were set up on the tidal flats fronting sea walls to attenuate wave energy and to

226   promote sediment accretion (Wolff et al., 2010). On these dike forelands, fast lateral

227   expansion at the expense of mud flats is observed combined with very high vertical accretion

228   rates of up to 18 mm/yr (Stock, 2011).

229 Meanwhile, the presence of a continuous dike line along most of the mainland coast of the

230 Wadden Sea inhibits the inland migration of the foreland marshes, which would be their

231 natural response to SLR and increased hydrodynamic energy. Wherever the marsh is laterally

232 eroding or vertical accretion rates in the pioneer and low marsh zones are below current SLR

233 rates, the marshes are squeezed in between the sea and the dike. This phenomenon, usually

234 referred to as "coastal squeeze", has been shown to intensify with accelerated sea level rise

235 and stronger storm activity (Bartholomä and Flemming, 2007; Doody, 2004; Flemming and

236 Nyandwi, 1994).

237

238 *3   Knowledge gaps in understanding of salt marsh dynamics*

239

240 Having evaluated the available literature related to vertical and lateral salt marsh dynamics,

241 we conclude that the general mechanisms of vertical salt marsh accretion and lateral salt

242 marsh development are well understood and described for homogenous salt marshes with a

243 constant sediment supply. Existing salt marsh models (e.g. Randerson, 1979; Krone, 1987;

244 Allen, 1990; French, 1993; D'Alpaos et al., 2007; D'Alpaos et al., 2011; Kirwan et al., 2010;

245 Marani et al., 2010; Mariotti and Fagherazzi, 2010; Mudd et al., 2004; Fagherazzi et al., 2006)

246 have proven their great potential for gaining process knowledge, since many of the involved

247 processes are hard to measure (Nolte et al., 2013). Most of these models, however, exhibit

248 shortcomings in the representation of spatial sedimentation patterns and with temporally

249   varying environmental boundary conditions (Andersen et al., 2011). As the main reasons for

250   these shortcomings we identify the following knowledge gaps:

251   1) Bio-physical interactions between the marsh vegetation and the hydromorphological

252   processes relevant for the vertical accretion processes on salt marshes are hardly investigated

253   yet (Temmerman et al., 2005; Neumeier and Amos, 2006; Marani et al., 2013). These

254   processes include the spatial influence of heterogeneous marsh vegetation on particle

255   flocculation, hence particle sizes and net sediment flux affecting vertical accretion rates.

256   Marani et al. (2013) have demonstrated the importance of such spatial heterogeneity for the

257   marsh development and concluded that these may affect the resilience of marshes against sea

258   level rise and sediment depletion.

259   2) Very little attention has been given to the effect of vegetation height in relation to

260   inundation height on sedimentation rates. While a few authors have compared the

261   hydrodynamic influences of emerging and submerged marsh vegetation (Temmerman et al.,

262   2005; Neumeier and Amos, 2006), nothing is known on how this ratio quantitatively influences

263   long-term sedimentation rates. Assuming a significant increase of depth-averaged flow

264   velocities once the marsh vegetation is completely submerged, one may expect a decrease of

265   depth-averaged settling velocities. This would be associated with lower sedimentation rates

266   than if a constant settling velocity is assumed. Specifically, this effect may be important if

267   changes in the tidal range and/or changes in storm patterns in combination with SLR result in

268   greater inundation depths.

269   3) Even though, it is well understood that the morphological development of salt marshes

270   primarily depends on local sediment supply, a thorough understanding of how the temporal

271   variability of this parameter affects the short-term and long-term development of coastal salt

272   marshes is not available (Andersen et al., 2011). Such temporal variations could be induced by

273   increased hydrodynamic energy, e.g. as a consequence of an increased tidal range or a phase

274   of stronger storm activity, or by changes in the sediment dynamics of the surrounding coastal

275   environment, such as the sediment resuspension from tidal flats or the import of sediment

276   into the tidal basin. A range of conceptual numerical models is employed to investigate these

277   processes and their impacts on the lateral marsh development and the local sediment supply

278   of salt marshes (Marani et al., 2010; Mariotti and Fagherazzi, 2010; Tonelli et al., 2010).

279   However, none of these models has considered the large temporal variability in the stability of

280   tidal flat sediments.

281   A better understanding of these sedimentary processes could improve the reliability of

282   predictions for future salt marsh development and would help to evaluate whether observed

283   trends are a result of a long-term regime shift (e.g. triggered by SLR) or whether they are

284   induced by short-term variations in storm activity, for example (Schuerch et al., 2013;

285   Andersen et al., 2011).

286

287   **IV Sediment dynamics on the tidal flats and in the tidal basins**

288

289   *1   Sediment resuspension on tidal flats*

290

291 Sediment resuspension on tidal flats positively influences vertical accretion rates on salt

292 marshes through increased sediment availability (Callaghan et al., 2010). At the same time,

293 lateral erosion may be caused as a consequence of vertically eroding tidal flats and hence

294 decreasing wave attenuation in front of the salt marsh (Mariotti and Fagherazzi, 2010).

295 Sediment resuspension on tidal flats is a function of the erodibility of the sediment and the

296 prevailing shear stress (Mariotti and Fagherazzi, 2010). The process of sediment resuspension

297 starts when the prevailing shear stress induced by tide- or wind-driven currents as well as

298 (breaking) waves exceeds the critical shear stress of the sediment surface (Miller et al., 1977;

299 van Rijn, 1993; Andersen et al., 2007; Mariotti and Fagherazzi, 2010). In most locations the

300 wind wave-induced shear stress is the dominant term for erosion on tidal flats (Le Hir et al.,

301 2000; French et al., 2000). The erosion rate thereby depends on the change of the critical

302 shear stress within the sediment surface layer (Sanford and Maa, 2001).

303 *a Physical parameters affecting sediment stability.* The erodibility of sediments is directly

304 related to its grain size composition (Hjulström, 1955). For non-cohesive (sandy) sediments the

305 critical shear stress continuously increases with higher grain sizes (Soulsby and Whitehouse,

306 1997). For cohesive (muddy) sediments it increases with smaller particle sizes (Hjulström,

307 1955) and stronger consolidation (Postma, 1961).

308 In natural environments, sediments are mostly a mixture of non-cohesive sandy and cohesive

309 muddy material (Andersen et al., 2010). Depending on the mineralogy and grain size

310 composition of the sediment, the highest critical shear stress is found at mud contents of

311 about 30-50% (Le Hir et al., 2007; Mitchener and Torfs, 1996; Grabowski et al., 2011). Based on

312 laboratory experiments (Panagiotopoulos et al., 1997), Ahmad et al. (2011) show that the

313 critical shear stress moderately increases with higher mud contents up to a mud content of

314 about 50%.; above 70% it dramatically decreases. Similarly, Panagiotopoulos et al., (1997)

315 suggests a maximum critical stress at a mud content of 50%.

316 *b Grain size distribution in the tidal basins of the Wadden Sea.* As a consequence of land

317 reclamation and "coastal squeeze", the finest grain size fraction in vicinity of the mainland has

318 been depleted in comparison to pre-embankment conditions (Flemming and Bartholomä,

319 1997; Flemming and Nyandwi, 1994; Mai and Bartholomä, 2000). This depletion is intensified

320 in narrow tidal basins and is assumed to continue as a consequence of increased SLR and

321 storm activity (Bartholomä and Flemming, 2007; Flemming and Nyandwi, 1994; Mai and

322 Bartholomä, 2000). Under storm conditions, wave-induced resuspension of tidal flat sediments

323 and the following export of primarily fine-grained material (Bartholomä and Flemming, 2007;

324 Lettmann et al., 2009) as well as an increasing amount of coarse-grained sediments imported

325 into the tidal basin via suspended load transport are responsible for this trend (Lettmann et al.,

326 2009; Santamarina Cuneo and Flemming, 2000).

327 A continuing depletion of fine-grained sediments could lead to higher sediment instability on

328 the tidal flats with less than 30% fine-grained sediments at present, and to higher sediment

329 stability on tidal flats with currently more than 50% fine-grained sediments (Le Hir et al., 2007;

330 Mitchener and Torfs, 1996; Grabowski et al., 2011). Hence, it could affect the availability of

331 fine-grained sediments for the salt marshes.

332   *c Biological parameters influencing sediment stability.* The biotic activity in and on the

333   sediment is considered as a major factor mediating the mud content of the sediment via

334   deposition of micro-phytoplankton, production of micro-phytobenthos as well as pelletisation

335   of macro-zoobenthos (Andersen et al., 2010). Even more importantly, biological activity is

336   directly affecting the stability of the sediment (Reise, 2002).

337   Among the biological parameters influencing the stability of tidal flat sediments, particular

338   emphasis is given to the influence of benthic diatoms and cyanobacteria. In the Wadden Sea,

339   these have been shown to increase the sediment stability by the production of extracellular

340   polymeric substances (EPS) as well as colloidal carbohydrates and enhance local sedimentation

341   by direct trapping of suspended sediment (e.g. Andersen et al., 2010; Austen et al., 1999;

342   Lanuru et al., 2007; Paterson, 1989; Stal, 2010). The biomass of diatoms is restricted by the

343   availability of light and nutrients as well as by grazing and resuspension through the

344   macrozoobenthos. Highest concentrations are usually found in April and September (Andersen

345   et al., 2010) and on higher elevated tidal flats (Austen et al., 1999). It should, however, be

346   noted that benthic diatoms, occurring on the sediment surface only influence the critical shear

347   stress at the sediment surface, while they do not decrease the erosion rate, once the critical

348   shear stress has been exceeded (Andersen, 2001; Mariotti and Fagherazzi, 2010).

349   Another important biological influence on the erodibility of the tidal flats is the presence of

350   macrozoobenthos, either stabilizing or destabilizing the sediment surface (Knaapen et al.,

351   2003; Volkenborn et al., 2007). In the Wadden Sea, the lugworm (*Arenicola marina*), for

352   example, as one of the most prevalent macrobenthic animals, has been shown to increase the

353   erodibility of the sediment by intense bioturbation. This activity also inhibits the colonization

354   of potentially sediment-stabilizing species, such as the tube-building polychaetes *Polydora*

355   *cornuta* and *Lanice conchilega* (Lanuru, 2004; Volkenborn et al., 2009). In any case, benthic

356   macrofauna tends to increase the surface roughness therefore enhancing the erodibility of the

357   sediment (Lanuru, 2004). Some benthic macrofauna species, such as the mud snail *Hydrobia*

358   *ulvae* additionally increase the erodibility of the sediment indirectly by grazing the biofilms of

359   diatoms and producing fecal pellets that are easily erodible (Andersen, 2001; Andersen and

360   Pejrup, 2002).

361

362   *2   Flocculation processes and floc settling velocity*

363

364   The settling velocity of suspended sediment is generally considered as a key factor for the

365   sediment dynamics in an estuary or coastal lagoon (Mantovanelli, 2005; van Leussen, 1988;

366   Winterwerp, 2002). While in theory, the settling velocity of non-cohesive single particles is

367   shown to be a function of particle size only (Soulsby and Whitehouse, 1997), in reality it is

368   controlled by the aggregation of cohesive sediment particles into flocs (Krone, 1962). Changes

369   of sediment composition and suspended sediment concentrations affect flocculation processes

370   and hence settling velocities of the suspended sediment. While flocculation processes are

371   related to high spatial and temporal variability, a general approximation for the settling

372   velocity of flocs (or single particles) as a function of the floc/particle diameter and its density is

373   given by Stokes law (Rubey, 1933).

374 According to their size and synthesis, Eisma (1986) distinguishes between micro-flocs (<125

375 μm) and macro-flocs (<3-4 mm), built through collision of micro-flocs. The latter are much

376 larger, but less dense and more fragile than micro-flocs (Eisma, 1986). The organic content,

377 salinity, size of the single grains determine the flocculation ability, a measure of the probability

378 of particles to aggregate when colliding (Eisma, 1986; Kranck, 1973), while high sediment

379 concentrations and turbulent shear stress increase the probability of particle collision.

380 Meanwhile, the turbulent shear stress controls the maximum floc size by breaking up large

381 flocs in highly turbulent environments (Fig. 5) (van Leussen, 1994; Manning, 2004; Burban et

382 al., 1989; Winterwerp, 1998; Winterwerp et al., 2006). The turbulent shear stress threshold,

383 resulting in the maximum floc size and the highest settling velocities, is controlled by the

384 prevailing environmental conditions, such as, for example, the sediment composition

385 (Manning et al., 2010). It ranges from 0.3 N/m² to 0.6 N/m² (Manning, 2004; Winterwerp et al.,

386 2006; Manning and Dyer, 2007; Manning et al., 2010), whereas for microflocs it tends to be

387 higher (Fig. 5) (Manning, 2004; Manning and Dyer, 2007). Given that the suspended sediment

388 concentration is below the critical value where hindering effects for sediment settling occur

389 (Winterwerp, 2002), the settling velocity of a floc can be approximated by an exponential

390 relationship with the suspended sediment concentration (Burt, 1986).

391 Bioaggregation, the flocculation process mediated by organic matter, is considered as the most

392 important driver for flocculation in many coastal waters, including the Wadden Sea (Alldredge

393 and Silver, 1988; van Straaten and Kuenen, 1957). It is mostly driven by the influence of

394 microalgae, such as diatoms, binding mineral particles together, producing the so-called

395   marine snow. High rates of bioaggregation or production of marine snow are observed during

396   algae blooms with a corresponding increase in settling velocity of the suspended matter

397   (Alldredge and Gotschalk, 1989). Another important trigger for bioaggregation is the presence

398   of filter-feeding organisms, such as *Mytilus edulis* and *Cerastoderma edule* (van Straaten and

399   Kuenen, 1957; Verwey, 1952) or *Hydrobia ulvae* (Andersen and Pejrup, 2002). Through

400   biodepositon, these filter-feeders enhance sediment settling, while producing faecal pellets

401   and pseudo-faeces (Graf and Rosenberg, 1997; Kautsky and Evans, 1987). Therefore, particle

402   sizes and settling velocities increase in areas, where filter-feeding organisms are abundant

403   (Andersen and Pejrup, 2002).

404

405   *3   Flocculation processes on salt marshes*

406

407   Flocculation processes are different on vegetated marsh platforms in comparison to

408   unvegetated tidal flats (Graham and Manning, 2007). Due to a continuous decrease of flow

409   velocity and turbulent energy towards the inner parts of the marsh, larger sediment particles

410   and flocs are settling in the vicinity of the marsh edge and the tidal channels, while smaller

411   sediment particles are transported further into the marsh (Fig. 2) (Christiansen et al., 2000;

412   French and Spencer, 1993; Temmerman et al., 2004b; Temmerman et al., 2003a). A lower flow

413   velocity and turbulent energy in the inner part facilitates sedimentation due to reduced

414   vertical turbulent diffusion (Mudd et al., 2010; Neumeier and Amos, 2006; Shi et al., 1996), but

415   may also inhibit flocculation of fine-grained sediments and reduce settling velocities, since the

416   prevailing turbulent shear stress is usually lower than the critical turbulent shear stress for the

417   maximum floc size (Fig. 2) (Neumeier and Amos, 2006; Fagherazzi et al., 2012).

418   Furthermore, vertical flow gradients on vegetated salt marsh platforms (Leonard and Luther,

419   1995) affect sediment deposition on salt marshes (Neumeier and Amos, 2006). Flow velocity

420   and turbulent shear stress within the vegetation canopy are considerably lower than above the

421   vegetation or on the bare tidal flats, thereby promoting the settlement of cohesive sediment.

422   On the other hand, increasing flow velocity and turbulent shear stress above the vegetation

423   canopy inhibit sediment settlement through high flow velocities (Shi et al., 1996), while

424   simultaneously increasing the floc sizes through high turbulent shear stress (if those are not

425   exceeding the critical value) (Manning, 2004). During storm tides, such large flocs are travelling

426   over the marsh and reach higher marsh elevations or slowly sink into the vegetation canopy.

427   Thus, events of increased sediment settling may be observed there. Generally, flocculation

428   processes on salt marshes are controlled by the density and the morphology of marsh

429   vegetation (Graham and Manning, 2007) but are still unknown to a large extent.

430

431   *4   Knowledge gaps in understanding of tidal basin sediment dynamics*

432

433   Sediment dynamics on tidal flats are extremely complex and not fully understood yet.

434   Attempts to assess them in a spatio-temporal context are rare and usually subject to high

435   uncertainties (Widdows et al., 2004; Rahbani, 2011). In particular, the factors that determine

436   the grain size distribution on the tidal flats are not sufficiently known. This leads to the inability

437   to accurately estimate sediment resuspension and settling velocities (Wang et al., 2012).

438   Furthermore, the actual processes of sediment resuspension and flocculation are still highly

439   uncertain for sand-mud mixtures as well as the influence of biological parameters that show a

440   strong spatial and temporal variability. For modelling the morphological development of salt

441   marshes, these uncertainties pose a serious challenge, particularly because the long-term

442   sediment availability, its short-term temporal variations, and the sediment composition are

443   often unknown (Andersen et al., 2011).

444

445   **V   The sedimentary system of the Wadden Sea**

446

447   *1   The concept of a sand-sharing system*

448

449   The morphological elements of the Wadden Sea system can be described as a sand-sharing

450   system (Fig. 6), which distributes the sediment within the system according to prevailing

451   hydrodynamics and morphological conditions (CPSL, 2001). Through redistribution of the

452   sediment within the sand-sharing system, sediment required for the tidal flats to adapt to SLR

453   is removed from the ebb-tidal deltas and transported into the tidal basins by tide or wind

454   induced currents, and is therefore potentially available for deposition on the salt marshes

455   (Elias et al., 2007; Hofstede, 1999a). Wind and wave activity significantly modify the sediment

456   exchange between the ebb-tidal delta and the tidal basin by reducing the size of the ebb-tidal

457 delta through erosion and an increased shoreward sediment flux into the tidal basin (Hofstede,

458 1999b; Walton and Adams, 1976). The incoming sediment is distributed through (sub-)tidal

459 channels, from where adjacent tidal flats and salt marshes are inundated and supplied with

460 allochthonous sediment.

461

462 *2 Fine and coarse-grained sediment transport into the tidal basins*

463

464 As a consequence of the shore-normal energy gradient (i.e. decreasing current velocities

465 towards the inner tidal basin) and the so-called settling and scour lags (van Straaten and

466 Kuenen, 1957; Postma, 1961), fine-grained sediments are transported further into the tidal

467 basins, whereas the coarse-grained sediments tend to settle in the vicinity of tidal inlets

468 (Flemming and Nyandwi, 1994). The settling and scour lags are resulting from the transport of

469 the fine-grained sediment during its settling phase and higher current velocity needed to

470 resuspend a sediment particle from the seabed than to deposit it (van Straaten and Kuenen,

471 1957; Postma, 1961). These processes are considered as the most important ones for a net

472 import of fine-grained sediments into the tidal basins of the Wadden Sea (van Straaten and

473 Kuenen, 1958).

474 Additionally, the distortion of the tidal wave in coastal areas and the density-driven currents

475 between the North Sea and the Wadden Sea as well as the (de-)stabilizing effect of physical

476 sediment properties and benthic organisms are controlling the net amount of sediment

477 accumulating within the tidal basins (CPSL, 2010). When travelling in shallow water or along an

478   estuary or tidal basin, the distortion of the tidal wave induces shorter but stronger flood

479   currents and longer but weaker ebb currents (Dronkers, 1986; van der Spek, 1997). Stronger

480   flood currents (in comparison to the respective ebb currents) promote the import of coarse-

481   grained sediment via bed-load and/or suspended transport (Dronkers, 1986; van der Spek,

482   1997; van Kreeke and Hibma, 2005; Wang et al., 2012). Meanwhile, an elongated high slack

483   water period (in comparison to the previous and the following low slack water periods) may

484   enhance the net import via suspended load transport and the sedimentation of fine-grained

485   sediments (Dronkers, 1986; van Straaten and Kuenen, 1958; van Kreeke and Hibma, 2005). In

486   enclosed, gently sloping tidal basins with most of the tidal flats located below MSL, the

487   distortion of the tidal wave results in a larger import of fine-grained sediments compared to

488   open-shaped, steeply sloping tidal basins with most of the tidal flats located above MSL

489   (Dronkers, 1986; Pedersen and Bartholdy, 2006). The import of coarse-grained sediments is

490   smaller or even negative in tidal basins with large tidal flat areas and larger in tidal basins with

491   smaller tidal flat areas (Dronkers, 1986).

492   Due to these different drivers for the import of fine and coarse grained sediments, contrasting

493   fluxes may occur within a tidal basin during a single tidal cycle (van Kreeke and Hibma, 2005). A

494   net export of coarse-grained sediment in tidal basins with large tidal flat areas, for example,

495   may be balanced or exceeded by the import of suspended fine-grained sediments

496   (Ridderinkhof, 1997). Usually (during calm weather conditions), the suspended load import of

497   fine-grained sediment dominates over the net import of coarse-grained sediments (Wang et

498   al., 2012). During strong-wind and storm events, the import of coarse-grained sediments via

499   suspended load transport considerably increases, thereby exceeding the import of fine-grained

500   sediments (Santamarina Cuneo and Flemming, 2000; Van Goor et al., 2003).

501   Seasonal variations of the total sediment import into the tidal basin of the Wadden Sea are

502   induced by increased bioaggregation during spring and early summer algae blooms (Alldredge

503   and Gotschalk, 1989) as well as through biodepositon of filter feeding organisms, which are

504   more active during the warm summer months (Andersen and Pejrup, 2002). Density-driven

505   currents, induced by higher variations of fresh water input into the tidal basins and larger

506   seasonal temperature variations, may amplify the seasonal variations of the fine-grained

507   sediment import, although its relevance for the Wadden Sea is under debate (van Beusekom et

508   al., 2012; Wang et al., 2012).

509

510   *3   Sediment sources*

511

512   External sources of predominantly coarse-grained sediments other than the neighbouring tidal

513   basins are found on the foreshore, the seaward beaches, and in the dunes of the barrier

514   islands (CPSL, 2010). Most fine-grained sediments are supplied from riverine inputs such as the

515   Rhine or the Elbe River as well as from soft-rock erosion on the English East Coast (Gayer et al.,

516   2006) and presumably from ancient river valleys now located offshore (Dellwig et al., 2000).

517   Other sources of fine-grained sediment are atmospheric deposition, primary production, direct

518   fluvial input, and sediment from salt marsh erosion (Pedersen and Bartholdy, 2006; Pejrup et

519 al., 1997). These sources strongly determine the availability of fine-grained sediments in the

520 coastal North Sea and the import into the tidal basins of the Wadden Sea.

521 For most tidal basins in the Wadden Sea, sediment import from the coastal North Sea is the

522 largest contribution to the total fine-grained sediment inventory (Dellwig et al., 2000).

523 Pedersen and Bartholdy (2006), for example, found the import to vary between 52 to 82% in

524 four Danish tidal basins. Estimated net imports of fine-grained sediment vary between 0.10 g

525 m^{-3} (List tidal basin) to 0.53 g m^{-3} (Grådyb basin) for an average tidal cycle within a distance of

526 only 60 km, for example (Pedersen and Bartholdy, 2006).

527

528 *4   Trapping capacity of the tidal basins*

529

530 An important parameter influencing the net sediment transport into the tidal basin is their

531 trapping capacity. It is generally controlled by bed roughness and sediment stability, which are,

532 to a large extent, determined by biological activity. Especially where vegetation canopies such

533 as seagrass beds or salt marshes are present, but also where mussel beds and other reef-

534 building epibenthic organisms are found, currents are slowed down, sediment resuspension is

535 inhibited, and sediment accretion is enhanced. At the same time the sediment stability is

536 increased due to the binding forces of the roots and the presence of biofilms inhibiting

537 sediment resuspension (CPSL, 2010; Ward et al., 1984). Increased sediment stability

538 additionally amplifies the scour lag effect and thereby contributes to the import of fine-grained

539 sediments (Vos and van Kesteren, 2000).

540

541   *5   Knowledge gaps in understanding the sedimentary system of the Wadden Sea*

542

543   Looking into the future development of the salt marshes in the Wadden Sea, we identify the

544   availability of fine-grained sediments and their settling velocities on salt marshes to be

545   crucially important. These parameters largely depend on the amount and composition of

546   sediments being imported into the tidal basins and their erodibility, once deposited on the

547   tidal flats. Given the projected SLR for the Wadden Sea region, insufficient knowledge is

548   available about how the tidal flats will evolve in the future with respect to their elevation and

549   composition. One of the main reasons for this is the current practice of assessing the sediment

550   budgets of the different tidal basins per sediment fraction, rather than looking at the

551   combined cohesive and non-cohesive sediment budgets (Wang et al., 2012). Future modelling

552   approaches will need to concentrate on the total sediment budget, thereby integrating the

553   cohesive and non-cohesive sediments and their grain sizes. They additionally need to account

554   for the morphological differences between the various tidal basins and their trapping

555   efficiencies that are strongly controlled by the variable biological activity.

556   In this review, we studied the morphological processes within tidal basins consisting of

557   channels, tidal flats and salt marshes (Fig. 6). However, it should be noted that in large tidal

558   basins, subtidal flats comprise large areas (up to 60%). It is likely that the morphological

559   behaviour in this deeper zone is not the same as described for the intertidal areas. Hardly any

560   research has been performed on interactions between subtidal and intertidal flats on the

561   sediment budgets of the tidal basins, but doing so could possibly further improve the

562   understanding of the sedimentary system of the Wadden Sea.

563

564   **VI An integrated conceptual model for the Wadden Sea salt marshes**

565

566   By evaluating the available literature on hydromorphological processes directly and indirectly

567   affecting the development of the Wadden Sea salt marshes, we identify important interactions

568   between sedimentary processes taking place on salt marshes as well as on tidal flats and the

569   entire tidal basins. Knowledge gaps are identified that we consider responsible for the limited

570   ability of salt marsh models to predict the future development of the Wadden Sea salt

571   marshes. Partly, the existence of these knowledge gaps is due to the lack of reliable empirical

572   data, but also due to the high degree of complexity of the involved processes. However, for

573   estimating the future development of coastal salt marshes under the influence of projected

574   global sea level rise, these processes have to be accounted for in salt marsh modelling, since

575   they drive the temporal and spatial variability of sediment supplied to the salt marshes.

576   In order to overcome this issue and bring forward the development of salt marsh models, we

577   propose a conceptual model (Fig. 7) that integrates the most important interactions between

578   the fringing salt marshes and the neighbouring tidal flats and tidal basins. This model aims to

579   reduce the complexity of the system by identifying the processes that are directly responsible

580   the quantity and quality of the sediment supplied to the salt marshes. It draws the sediment

581   pathways that are relevant for the development of salt marshes and clarifies their role within

582   the morphological system of the Wadden Sea.

583

584   *1   Description of the conceptual model*

585

586   Sediment import during calm weather periods is dominated by the import of fine-grained

587   sediments via suspended sediment load and a minor contribution of coarse-grained sediment

588   import via bed-load and/or suspended load transport (Fig. 7, 2). When onshore winds increase

589   (inducing set-up of the water level), more coarse-grained sediments are imported via

590   suspended sediment load, exceeding the import of fine-grained sediments during storm events

591   (Fig. 7, 1). While flooding the tidal flats, parts of these suspended sediments are deposited on

592   the tidal flats (Fig. 7, 5). The net sediment accumulation is mainly determined by the

593   topography and the bed roughness of the tidal flats, which strongly depend on the physical

594   sediment characteristics as well as the epibenthic structures on the tidal flats (Fig. 7, 3).

595   Similarly, the physical sediment characteristics of the tidal flats and the biological activity on

596   them determine the erodibility of the tidal flat sediments (Fig. 7, 3+4). The eroded sediment

597   from the tidal flats and from the marsh scarp is either exported from the tidal basin via the

598   tidal channels (Fig. 7, 5) or transported onto the salt marsh during strong wind or storm events

599   (Fig. 7, 6). The composition of this sediment is rather fine, but depends on the characteristics

600   of the tidal flat and the prevailing hydrodynamic conditions. Meanwhile, a direct input of

601   sediment from the tidal channel towards the salt marsh is predominantly occurring during

602   strong wind and storm events (Fig. 7, 7), whereas the composition of this sediment may be

603   considerably coarser than the sediment that is eroded from the tidal flats. Once transported

604   onto the salt marsh, a spatial pattern regarding the suspended sediment characteristics is

605   observed (Fig. 7, 8+9). More and coarser sediments are found towards the seaward part of the

606   marsh or in vicinity of the marsh creeks (Fig. 7, 8) compared to the inner part of the marsh,

607   where less and finer sediments are found in suspension (Fig. 7, 9). The differences in

608   suspended sediment characteristics induce higher settling velocities in the seaward part of the

609   marsh, whereas these may vary vertically. Due to the higher turbulence level above the

610   vegetation, flocculation is promoted, while the higher flow velocities allow the settlement of

611   only the largest flocs/particles. In contrast, the floc size within the vegetation is smaller due to

612   the lower turbulence level, but strongly reduced flow velocities allow the small particles and

613   flocs to settle (Fig. 7, 8+9).

614

615   *2   Suggested use of the proposed conceptual model*

616

617   The proposed conceptual model has been developed in order to reduce the complexity of

618   representing the involved processes in the (sub-)tidal sediment dynamics and thereby improve

619   the estimation of boundary conditions and model parameters for salt marsh models. An

620   implementation of this conceptual model includes the coupling of existing models that

621   specifically address the different processes as shown in figure 7. Such a coupled modelling

622   approach could be used to investigate how changes in the large-scale sedimentary system of

623   the Wadden Sea would affect the development of the fringing salt marshes. Furthermore, the

624   model could be used to estimate the influence of long-term (SLR) as well as short-term sea

625   level variations (storm activity) on the future survival of the salt marshes. Besides the region of

626   the Wadden Sea, the model could also be applied to comparable sedimentary systems, such as

627   coastal lagoons with active inlets behind a coastal barrier.

628   Based on the proposed conceptual model, an integrated modelling approach could more

629   efficiently capture the process interactions within the tidal basin - tidal flat - salt marsh

630   continuum and thereby overcome some of the above identified knowledge gaps. For example,

631   it could investigate and, to some extent quantify, the influence of a gradual increase of global

632   and regional MSL in the coming century (Meehl et al., 2007; Vermeer and Rahmstorf, 2009;

633   Wahl et al., 2010) on the sediment availability for coastal salt marshes as described in the

634   following example:

635   A gradual SLR increases the demand for fine and/or coarse-grained sediments on the tidal flats

636   and the demand for fine-grained sediments for the salt marshes to keep pace with SLR. The

637   fine-grained sediment budget will be affected by a modified distortion of the tidal wave within

638   the tidal basin. Accelerated sea level rise with tidal flats lagging behind in net accretion would

639   increase the proportion of shallow subtidal areas at the expanses of intertidal flats. A modified

640   tidal wave distortion could favour the import of fine-grained sediments during calm weather

641   conditions, increasing, in turn, the sediment availability for the fringing salt marshes. The

642   single-grain settling velocities might decrease and the flocculation ability of the sediment

643   particles might increase correspondingly.

644   In contrast, increasing storm surge heights and a possible moderate increase of storm activity

645   (Weisse et al., 2006; Weisse et al., 2012; Woth et al., 2006), could lead to a stronger net export

646   of fine-grained sediments. In the long-term, this could amplify the trend towards coarser

647   sediments in the Wadden Sea and decrease the sediment availability for salt marshes. With a

648   coarser sediment fraction available, the single-grain settling velocities would increase and the

649   flocculation ability of the sediment would decrease.

650

651   **VII Conclusions**

652

653   The above conceptual model is proposed as a framework for salt marsh modellers in order to

654   facilitate the integration of important interactions between processes taking place within tidal

655   basins, tidal flats, and on salt marshes for estimating future salt marsh development. It

656   graphically displays the following more generic conclusions that we draw from this study:

657   1) Sediment availability for salt marshes depends on the morphology of tidal basins and on

658   whether future SLR will be accompanied by increasing storm activity or not.

659   2) Changing grain-size distribution in response to climate change potentially affects the salt

660   marsh development by modified sediment availability and changes particle/floc settling

661   velocities.

662   3) Flocculation processes on salt marshes are strongly influenced by the available sediment

663   and its grain-size distribution as well as the structural dynamics of salt marsh vegetation and

664   may considerably influence the spatial accretion patterns and the vertical accretion rates.

665　Existing salt marsh models are well capable of identifying important processes dominating salt

666　marsh accretion. However, important processes in the tidal basins and on its tidal flats that

667　determine the local sediment availability and sediment characteristics are not yet sufficiently

668　incorporated.

669

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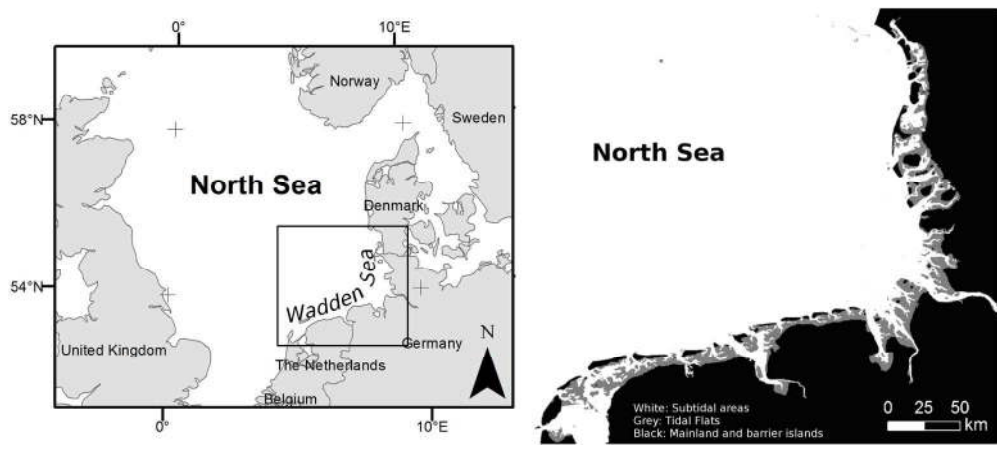
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Figure 1: Location of the Wadden Sea along the south-eastern coast of the North Sea (left). The Wadden Sea area consists of the subtidal areas (white), the tidal flats (grey) and the barrier islands and mainland coasts (black) (right).
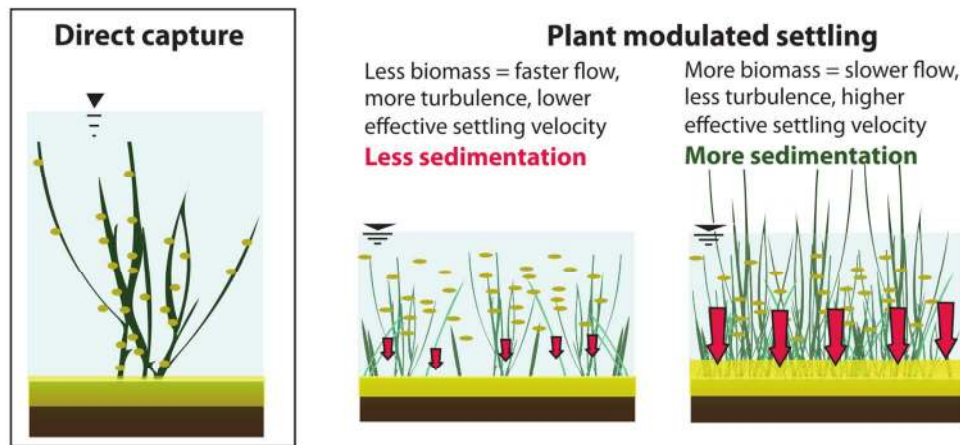160x70mm (300 x 300 DPI)

Figure 2: Vegetation effects leading to enhanced allochthonous marsh accretion. Source: Fagherazzi et al., 2012.
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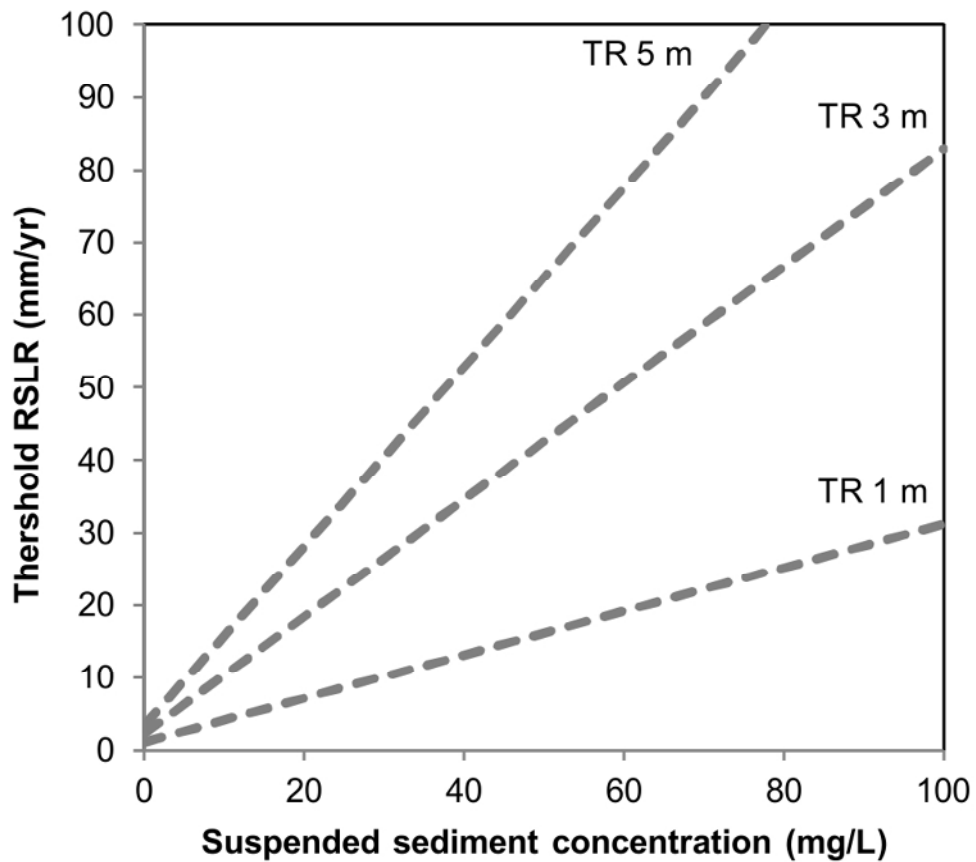42
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Figure 3: Threshold relative SLR rates for the survival of salt marshes as a function of tidal range (TR) and local sediment availability (suspended sediment concentration), modelled with five different salt marsh models. Dashed lines indicate three different tidal regimes (1 m, 3 m, and 5 m). Source: Modified after Kirwan et al., 2010.
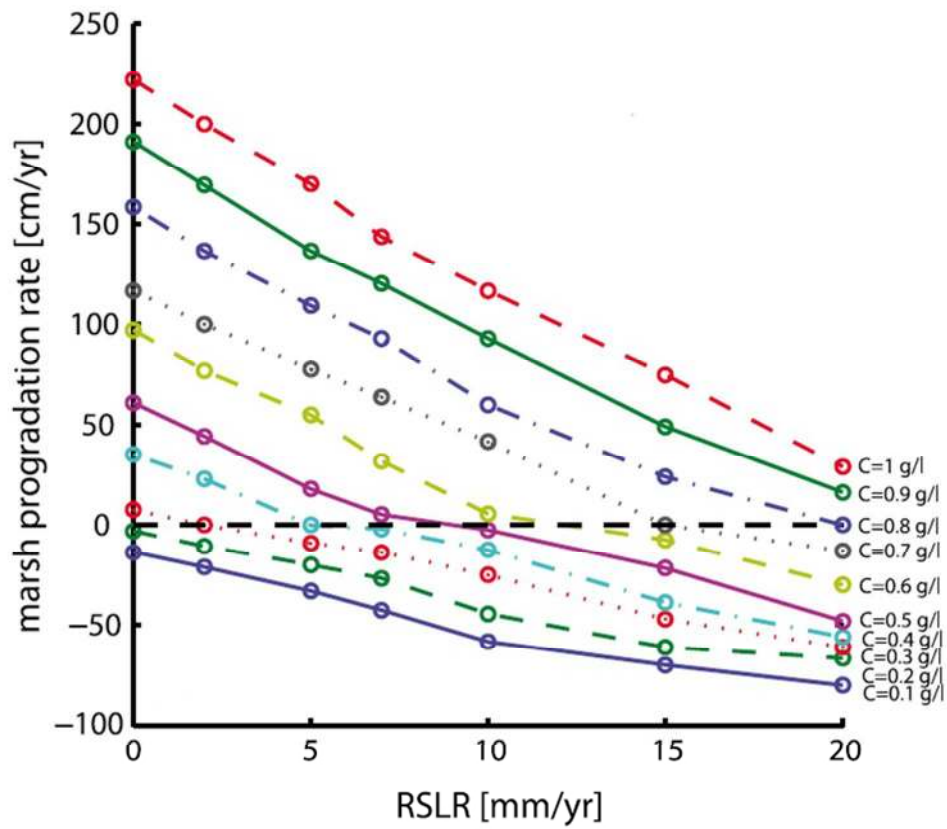83x73mm (300 x 300 DPI)

Figure 4: Lateral marsh dynamics in response to RSLR and sediment availability (C). Source: Mariotti and Fagherazzi, 2010.
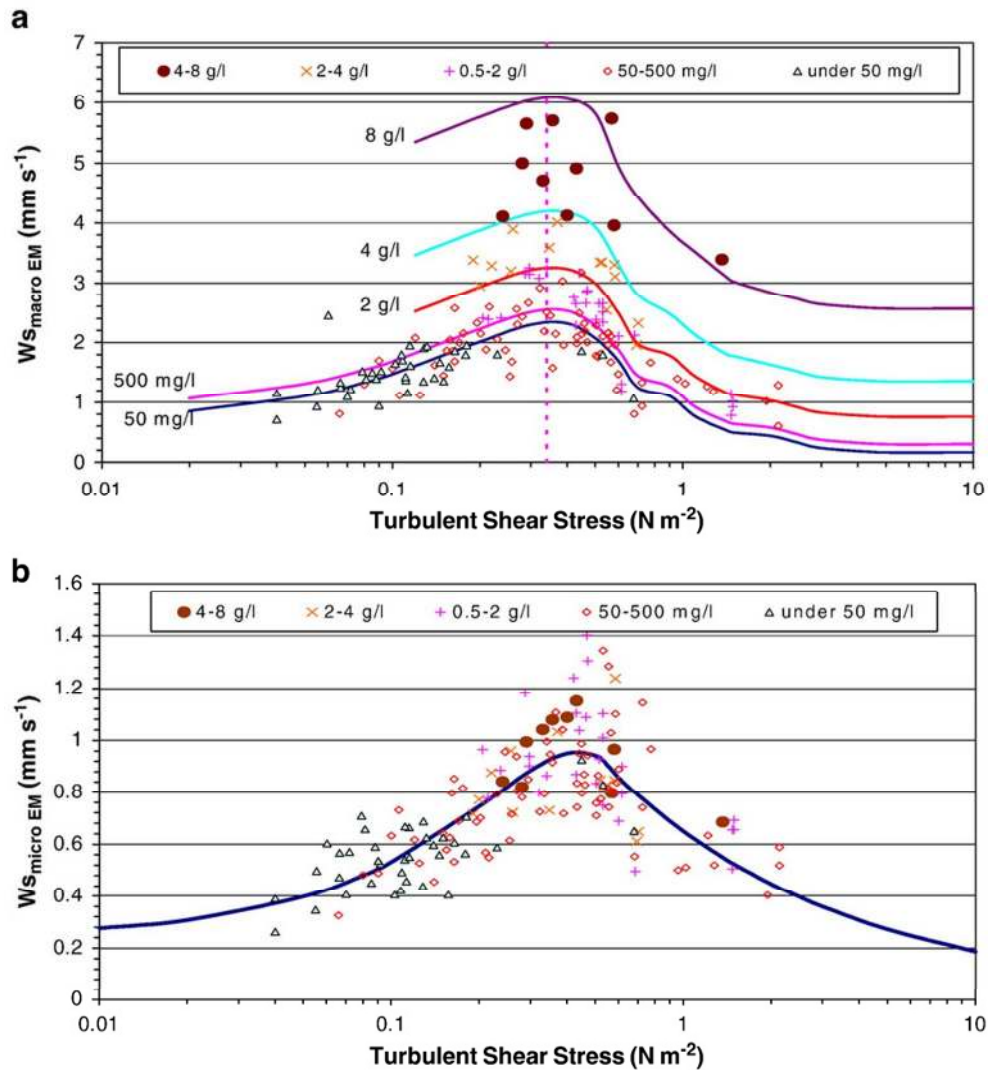83x72mm (300 x 300 DPI)

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Figure 5: Floc settling velocity (w_s) as a function of turbulent shear stress and suspended sediment concentrations for macro-flocs (a) and micro-flocs (b) assessed for several European estuaries. Source: Manning and Dyer, 2007.
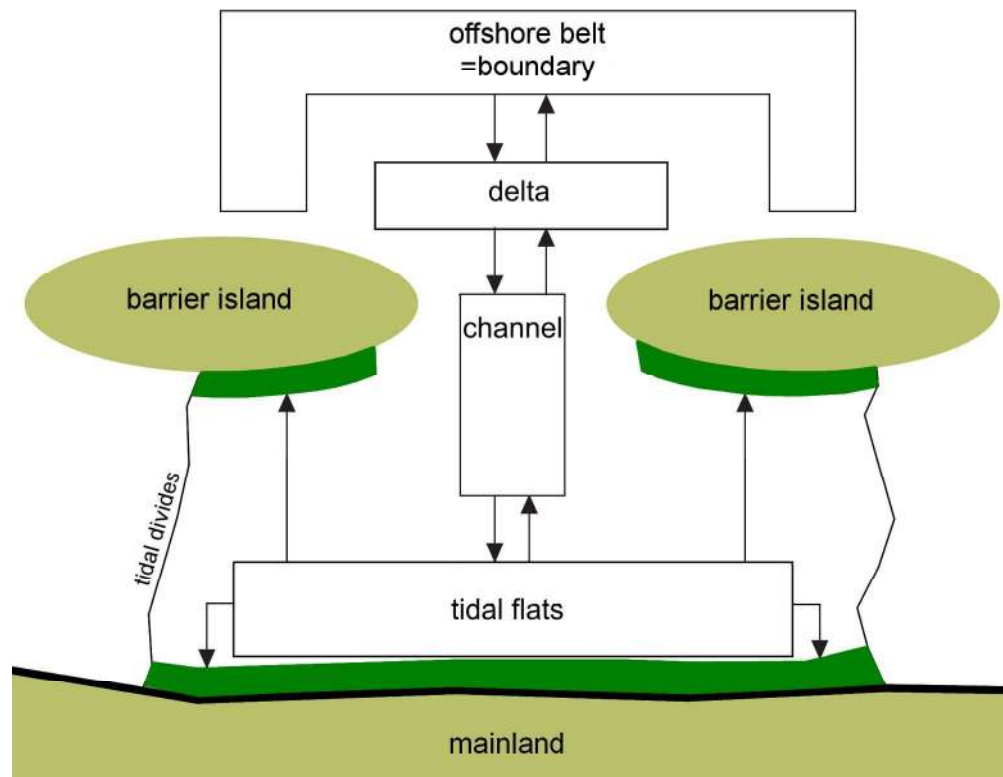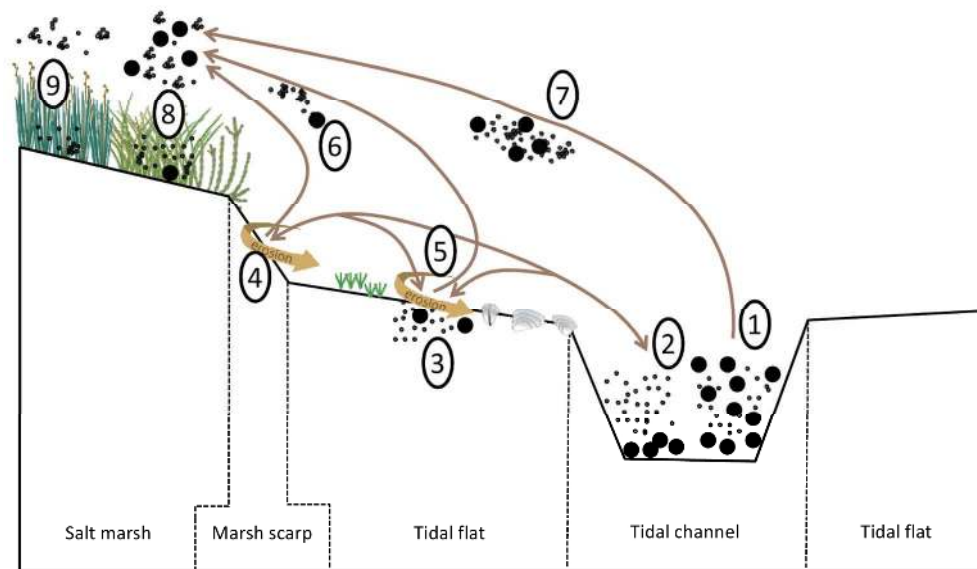160x174mm (300 x 300 DPI)

Figure 6 (modified after Kragtwijk et al., 2004): Morphological elements of the sand-sharing system for one tidal basin, as schematized by the "Aggregate scale morphodynamic model of integrated coastal systems" (ASMITA) model. The fringing salt marshes are added as an additional morphological element that act as a sediment sink for the tidal basin. Source: Modified after Kragtwijk et al., 2004.
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1) Sediment influx through tidal channel during storm events (coarser sediment)
2) Sediment influx through tidal channel during calm periods (finer sediment)
3) Sediment resuspension on tidal flats affected by physical (e.g. grain size) and biological (benthic flora and fauna) sediment properties.
4) Sediment resuspension at marsh edge (controlled by physical and biological parameters as well as the slope and height of the scarp)
5) Sediment exchange between tidal channel, tidal flat, and salt marsh
6) Transport of sediments resuspended from the tidal flats and the marsh edge towards the salt marsh
7) Direct sediment transport from tidal inlet to salt marsh during storm events
8) Marsh accretion in seaward part of the marsh (more and coarser sediment)
9) Marsh accretion in landward part of the marsh (less and finer sediment)

Figure 7: Conceptual model of sediment dynamics between the different morphological units in the Wadden Sea (tidal channel, tidal flats, salt marshes; subtidal flats have been omitted because of gap in knowledge). 160x134mm (300 x 300 DPI)