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► **To cite this version:**

M.J. Baptist, M.F. Leopold. The effects of shoreface nourishments on and scoters in The Netherlands. Marine Environmental Research, 2009, 68 (1), pp.1. 10.1016/j.marenvres.2009.03.003 . hal-00487741

HAL Id: hal-00487741

<https://hal.science/hal-00487741>

Submitted on 31 May 2010

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Accepted Manuscript

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PII: S0141-1136(09)00030-0

DOI: [10.1016/j.marenvres.2009.03.003](https://doi.org/10.1016/j.marenvres.2009.03.003)

Reference: MERE 3323

To appear in: *Marine Environmental Research*

Received Date: 30 December 2007

Revised Date: 3 March 2009

Accepted Date: 4 March 2009



Please cite this article as: Baptist, M.J., Leopold, M.F., The effects of shoreface nourishments on *Spisula* and scoters in The Netherlands, *Marine Environmental Research* (2009), doi: [10.1016/j.marenvres.2009.03.003](https://doi.org/10.1016/j.marenvres.2009.03.003)

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The effects of shoreface nourishments on *Spisula* and scoters in The Netherlands

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Abstract

The coast of The Netherlands is protected by nourishing sand. Generally, two different techniques are used, beach nourishment and shoreface nourishment. The latter technique supplies sand at a water depth of about 5 to 8 metres in the surf zone, and has been used on a regular basis since 1997 with increasing volumes since 2001. Observations on the bivalve mollusc *Spisula subtruncata* that was abundant before 1997 and a key food species for wintering seaduck show a decline since 2001. This coincided with a decrease in the abundance of the Common Scoter *Melanitta nigra*, the most numerous wintering seaduck off the Dutch coast. These observations raised concern about shoreface nourishments. This study analyses the timing and locations of shoreface nourishments in combination with *S. subtruncata* abundance and spatial distribution. Against the expectation, no causal relationship was found between the decline of *S. subtruncata* and shoreface nourishments. Other causes, such as climate change, fisheries, unsuccessful settlement or predation of spatfall are more likely behind the decline of *Spisula* along the Dutch coast.

Key words: Shoreface nourishment, *Spisula subtruncata*, *Melanitta nigra*, North Sea, Seabirds, Benthos, Sediments

1 Introduction

2 In The Netherlands, coastal protection offered by beaches and dunes is main-
3 tained by nourishing sand. At first, this was achieved by supplying sand di-
4 rectly onto the beach but later shoreface nourishment became the preferred
5 technique (Roelse, 2002; Grunnet and Ruessink, 2005; Klein, 2005; Steijn,

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2005). Shoreface nourishment supplies sand in between the outer breaker bars along the coast, or offshore from the outer bar, at water depths of about 5 to 8 metres. The supplied sand moves gradually towards the coast by the natural action of waves and currents, re-establishing the original coastline prior to erosion (Van Duin et al., 2004). Since 1997, shoreface nourishments are applied regularly and since 2001 increased volumes of sand have been supplied, Fig. 1.

Sand nourishments can affect the ecosystem in various ways (Van Dalfts and Essink, 1997; Speybroeck et al., 2006). Direct effects are the burial of benthic species under a layer of sand. In the direct vicinity suffocation of benthos can occur due to the settling of a plume of suspended particles. A plume of fine particles may also affect primary production and the foraging success of filter-feeding benthos, fish and birds. In addition there might be disturbance by noise and ship manoeuvring. Indirect effects are habitat change, such as altered morphology and sedimentology. This may also change habitat characteristics such as penetrability, compactness, and organic matter and silt content.

In 1993 a shoreface nourishment was applied as large-scale pilot experiment along Terschelling. Possible ecological effects were extensively monitored (Tydeman, 1994; Van Dalfts and Oosterbaan, 1996; Van Dalfts and Essink, 1997). It was concluded that there were mainly short-term, local effects as a result of burial of benthic species. A recovery of the benthic fauna was reached after two years, with the exception of long-lived species of molluscs and echinoderms. Particular attention was paid to *Spisula subtruncata*, a bivalve that formed the staple food source for the Common Scoter (*Melanitta nigra*) (Leopold et al., 1995; Degraer, 1999; Degraer et al., 2007). *Spisula subtruncata* is found primarily in fine sands of about 200 μm in the lower shoreface at water depths of about 5 to 20 metres (Baptist et al., 2006; Craeymeersch and Perdon, 2006; Degraer et al., 2007). In their study, Van Dalfts and Essink (1997) gave a warning: "[...] shoreface nourishment may very well strike important *Spisula* banks, and then pose a serious risk to the survival of wintering seaducks".

Spisula surveys in Dutch coastal waters have been conducted since the 1990s (Leopold, 1996; Craeymeersch and Perdon, 2006). *Spisula* was very abundant along large parts of the Dutch coast in the 1990s, but during the period 2000 - 2005 numbers declined. The total biomass in 2005 was the lowest found since 1995, and has only slightly increased in later years (Craeymeersch and Perdon, 2006; Goudswaard et al., 2008). The decline in total *Spisula* abundance coincided with the increase in shoreface nourishments, Fig 1. Moreover, the numbers of overwintering Common Scoters also showed a decline in recent years, Fig. 2. This raised concern about the ecological effects of shoreface nourishments, particularly after the warning of Van Dalfts and Essink (1997).

There is no statistically significant correlation between declining *Spisula* abundance and increasing nourishment volumes (for untransformed data: $r = -0.33$, two tailed probability = 0.29). However, the coincidence implies a possible

causal relationship. Therefore, this study aims at assessing the timing and locations of shoreface nourishments and their relation with the spatial and temporal distribution of *Spisula subtruncata* and the consequences for the Common Scoter.

2 Material and Methods

We first made an inventory of underwater sand nourishment projects, gathering data on their location, extent, date, type and volume, Table 1. Sand nourishments below the water surface were already applied before the pilot experiment in 1993, but these were *channel slope* nourishments instead of *shoreface* nourishments (Roelse, 2002). Shoreface nourishments are applied to feed the morphologically active breaker bar system in front of beaches in order to shift the coastline seawards. Channel slope nourishments were applied to halt onshore migration of tidal gullies. In recent years, shoreface nourishments became more and more common along the Holland and Wadden coasts, Fig. 3.

Two data sets of *Spisula* surveys have been combined. One set is a yearly *Spisula* survey of the National Institute of Fisheries Research (RIVO), now Wageningen Institute of Marine Resources and Ecosystem Studies (IMARES), which covers the entire Dutch coast from 1995 onwards. Yearly in April and May, more than 800 bed samples are taken, with a sample area of 15 m² for the majority of the samples (Craeymeersch and Perdon, 2006). Bed samples were taken with a bottom cutting dredge, with the exception of the Voordelta where a small suction dredge was used (Craeymeersch and Perdon, 2006). The second data set consists of surveys carried out by the Institute of Forest and Nature Research (IBN-DLO), now IMARES as well, from 1994 to 1999. The latter surveys focused mainly on the northern coast of The Netherlands and were carried out with a Van Veen grab (Leopold, 1996). The combination of both sets resulted in maps of *Spisula* densities along the Dutch coast down to -20 m Dutch Ordnance Level (NAP) from 1994 onwards. In the years before 1994 some smaller surveys have been carried out (Craeymeersch, 1992; Leopold, 1993) and washed-up *Spisula* has been counted (Gmelig Meyling and De Bruyne, 1994) as an indication of the occurrence of offshore banks. These data, added with the fact that *Spisula* fisheries have been active since 1985, show that *Spisula subtruncata* was abundant along the Dutch coast at least from 1985 onwards.

The RIVO data set distinguishes 0-year and adult *Spisula* based on ring-counts on the shells. The 0-year class is the spatfall of the year before sampling. In the IBN-DLO data set, this division was made post hoc on the basis of shell size; animals smaller than 15 mm shell length were considered 0-year specimens.

With Inverse Distance Weighting (Shepard, 1968) the original point data

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4 were interpolated, and extrapolated to the line of mean tide height, to yield
5 complete coverage of *Spisula* density (numbers per m²) for the entire Dutch
6 coastal zone. The amount of overlap between nourished areas and *Spisula*
7 banks proved to be highly variable in space and time. *Spisula* banks occur at
8 least down to the -20 m NAP depth contour and up to the surf zone where
9 nourishments take place. Therefore, the *Spisula* density was determined for:
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13 (1) The location of the nourishment itself (see Fig. 3). Sampling did not in all
14 cases take place close enough inshore to cover the nourishment locations.
15 This implies that the resulting distribution is based on extrapolation.
16 (2) An extended location consisting of the nourishment location extended
17 down to the -20 m NAP depth line. In this way *Spisula* abundance in the
18 nourished coastal section is represented. This extension was not carried
19 out for locations in the Voordelta-area where tidal channels are close to
20 the shore.
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24 For each year between 1994 and 2005 the average density of 0-year and adult
25 *Spisula* was determined for each of the 38 shoreface nourishment locations
26 and their extended locations. The temporal development of *Spisula* was then
27 analysed and compared with the year of the shoreface nourishment to search
28 for possible strong shifts in abundance.
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32 33 34 **3 Results**

35 36 37 38 *3.1 Regional Spisula occurrence*

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41 Figure 4 shows the biomass of adult *Spisula* and the coincidence with nour-
42 ished volumes for four regions along the Dutch coast. This figure shows a
43 similar relationship as Fig. 1; *Spisula* biomass decreased when shoreface nour-
44 ishment volumes increased.
45

46 Along the Wadden coast, the first nourishment since the pilot experiment in
47 1993 was carried out off the coast of Ameland oost in 1998. This 2.5 Mm³
48 nourishment is likely to have had local effects, but our data show that in later
49 years *Spisula* biomass along the Wadden coast remained high. Our data fur-
50 ther show that the high 2001 biomass resulted from a successful recruitment in
51 2000, which occurred off the Wadden islands Ameland and Schiermonnikoog.
52 In 2001 a 1 Mm³ nourishment took place in the Wadden region. The next year,
53 the adult biomass decreased by 85%. However, this nourishment was carried
54 out off the island of Vlieland, where along its entire coast *Spisula* was never
55 abundant. Direct effects of the nourishment are thus excluded. Indirect effects
56 affecting an area of approximately 300 km² at a distance of 50 km away are
57 considered highly unlikely, since earlier nourishments in 1993 and 1998 did not
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4 128 have similar effects off the Wadden coast. In 2002 a 5.4 Mm³ nourishment was
5 129 applied at Texel, far away from the *Spisula* banks of Ameland and Schiermon-
6 130 nikoog, which were still present, but at lower densities. In later years, *Spisula*
7 131 gradually disappeared.

8
9 132 Along the Noord-Holland coast, nourishments have been applied each year
10 133 starting in 1998. The results of the 1998 *Spisula* survey showed a very low
11 134 biomass compared to 1997. Still, the 1998 Noordwijk nourishment took place
12 135 in an area with one of the few *Spisula* banks in this section, and most likely
13 136 has had effects, Fig. 5. However, the bulk of *Spisula* in 1997 was found off
14 137 Petten approximately 10 km offshore. This offshore bank, situated at more
15 138 than 50 km distance from the Noordwijk nourishment location had disap-
16 139 peared in 1998, Fig. 4, but given the large distance to the nourishment site, a
17 140 causal relationship seems unlikely. In 1999 and 2000 nourishments were car-
18 141 ried out in Egmond and Bergen aan Zee, much closer to the Petten *Spisula*
19 142 bank. In 2001, *Spisula* numbers off Petten again reached high values, resulting
20 143 from the succesful recruitment of 2000. Therefore any possible effects of the
21 144 nourishments do not seem to be permanent. In 2002, two nourishments were
22 145 applied at Noordwijkerhout and Camperduin. The *Spisula* banks were still
23 146 found offshore at Petten, but their biomass decreased and subsequently they
24 147 disappeared during a period in which nourishments continued.

25 148 The first Zuid-Holland coast nourishment was applied in autumn 1997 at Ter
26 149 Heijde. In that year, *Spisula* biomass along the Zuid-Holland coast was rel-
27 150 atively high due to a successful recruitment in 1996, but was concentrated
28 151 in the northern part of Zuid-Holland, away from Ter Heijde. Similar to the
29 152 events in Noord-Holland, *Spisula* in 1998 declined, recovered in 2001 and then
30 153 almost disappeared.

31 154 The first Voordelta coast nourishments were applied in 1987 and 1991 at Kop
32 155 van Schouwen. They were followed by nourishments in 2000 and 2001 off the
33 156 land reclamation Maasvlakte. In the meantime, *Spisula* reached high biomass
34 157 in 1996 and 1997, but since then it has almost disappeared.

35 36 37 38 39 40 41 42 43 44 45 158 *3.2 Local Spisula occurrence*

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49 159 Figure 5 presents the *Spisula* densities for 0-year and adult specimens for a
50 160 selection of eight out of 38 nourishment locations (cf. method 1), presented in
51 161 chronological order of nourishment occasions. Their locations are depicted in
52 162 Fig. 3. Complete data for all locations (for methods 1 and 2) are presented in
53 163 Tables 2 and 3. *Spisula subtruncata* can be found locally in dense banks, and
54 164 densities over 50 per m² are typified as 'banks'.

55 165 **Terschelling 1993.** In the years following the nourishment in 1993 a recovery
56 166 of *Spisula* has occurred, however, *Spisula* abundance has been greatly reduced
57 167 since 2004. This shoreface nourishment of 2 Mm³ was applied over a length
58 168 of approximately 4 km in between two breaker banks at a depth of -5 to -8

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4 169 m NAP, at a distance of 800-1400 m from the beach pole line (Van Dalssen
5 170 and Essink, 1997). At that time there was a large *Spisula* bank present off
6 171 the Terschelling coast. This bank stretched out over a length of about 20 km.
7 172 The highest densities ($>1000\text{ m}^{-2}$) were found at approximately 2 to 4 km
8 173 from the coast, at depths of -9 to -15 m NAP (Leopold, 1996). The shoreface
9 174 nourishment was, therefore, not applied in the area with the highest densities,
10 175 and has only buried *Spisula* at the landward fringe of the bank.

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13 176 **Ter Heijde 1997.** *Spisula* did occur here in the early 1990s, but was no longer
14 177 present at the time of the nourishment.

15 178 **Noordwijk 1998.** This 1.3 Mm^3 nourishment was applied on top of a *Spisula*-
16 179 bank according to our interpolated data. Exact data on this are not available,
17 180 since direct monitoring of *Spisula* on-site has not been carried out. *Spisula* did
18 181 not recover in the years following this nourishment.

19 182 **Ameland oost 1998.** This 2.5 Mm^3 nourishment was applied at a depth
20 183 of -5 to -7 m NAP, just outside the surf zone (Steijn, 2005). The surveys in
21 184 1998 show highest densities of *Spisula* at depths of -6 m NAP and deeper.
22 185 The nourishment was located on the landward side of the *Spisula* habitat,
23 186 but must have covered part of it. A recovery has been observed, based on a
24 187 successful spatfall in 1999. However, since 2003, the *Spisula* bank no longer
25 188 exists. Our results furthermore show that in the 1990s, *Spisula* banks were
26 189 located further away from the coast than in later years.

27 190 **Bergen aan Zee 2000.** This 1 Mm^3 nourishment was located in an area with
28 191 high densities of 0-year *Spisula*, which stretched further offshore as well, ac-
29 192 cording to our interpolated data. In 2001 high densities of adult *Spisula* were
30 193 observed, but these gradually disappeared in later years.

31 194 **Groote Keeten - Zwanenwater 2003.** This 2.57 Mm^3 nourishment was lo-
32 195 cated in an area where high densities of *Spisula* were found until 2001. *Spisula*
33 196 therefore had disappeared before the nourishment was applied.

34 197 **Texel Molengat 2003.** This area contained very rich *Spisula* banks in 1998
35 198 and 1999. These were heavily fished (Leopold, 1999) and have disappeared by
36 199 2000, before the nourishment was applied.

37 200 **Texel De Slufter 2004.** At this location rich *Spisula* banks in 1998 and 1999
38 201 were found. *Spisula* had disappeared well before the nourishment was applied.
39 202

40 203 **4 Discussion**

41 204 *4.1 Implications to Common Scoters*

42 205 There has been a general increase of numbers of Common Scoters wintering
43 206 along the east Atlantic coast in the early 1990s, followed by a decline (ICES,
44 207 2005). This decline was marked in the Netherlands and Belgium where the diet

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4 208 was mainly *Spisula subtruncata*, which also declined in abundance (Degraer
5 209 et al., 2007; Goudswaard et al., 2008). Numbers of Common Scoters did not
6 210 decline in France, where *Spisula* probably was far less important, but num-
7 211 bers did decline sharply in northwest Portugal, where their diet is presently
8 212 unknown (ICES, 2005). The decreasing trend in numbers of Common Scot-
9 213 ers in The Netherlands since the 1990s (Fig. 2) is attributed to the declining
10 214 availability of their staple food source, *Spisula* (Leopold et al., 1995; Leopold,
11 215 1996, 1999; Fox, 2003; ICES, 2005). The distribution of Common Scoters in
12 216 the coastal zone of The Netherlands used to be determined by the presence
13 217 of dense banks of *Spisula*. In 1987 the majority of Scoters was present along
14 218 the Zuid-Holland coast north of Noordwijk. From 1991 to 1993 large groups
15 219 were first found along Schiermonnikoog, but gradually they shifted towards
16 220 Ameland and Terschelling (Leopold, 1996). Here, *Spisula*-banks were present
17 221 but they were heavily fished, which resulted in Scoters leaving for the Noord-
18 222 Holland coast, off Petten (Leopold, 1996). In the following years, 1994 and
19 223 1995, Common Scoters flew back and forth between Ameland/Terschelling
20 224 and Noord-Holland, but now both areas were fished. The severe winters of
21 225 1995/1996 and 1996/1997 brought ice-cover in the coastal waters north of the
22 226 Wadden-islands and a large mortality of *Spisula* and other benthic macrofauna
23 227 (Armonies et al., 2001). The scoters moved to Noord-Holland again. In 1999
24 228 the densest bank of *Spisula* was located offshore of southwest Texel. This bank
25 229 was fished away in May 1999 (Leopold, 1999) and did not recover. The scot-
26 230 ers retreated to their favorite areas Terschelling and Ameland, where the last
27 231 banks of *Spisula* were present. Nowadays, *Spisula* has (almost) disappeared
28 232 and this clearly affects the coastal population of Common Scoters. Although
29 233 scoters can feed on *Ensis americanus* as an alternative food source, these bi-
30 234 valve molluscs are apparently an inferior prey (Leopold and Wolf, 2003; Wolf
31 235 and Meininger, 2004; Skov et al., 2008), because of their awkward shape and
32 236 their longer handling time.

33 34 35 36 37 38 39 40 41 42 43 44 237 4.2 *The decline of Spisula*

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47 238 If shoreface nourishments have not caused the decline of *Spisula*, and subse-
48 239 quently scoters, what then was the cause? As with many other benthic species
49 240 in the marine environment, the spatial and temporal distribution and abun-
50 241 dance of *Spisula* is highly variable (Hagmeier, 1930; Degraer, 1999; Degraer
51 242 et al., 2007). Cardoso et al. (2007) suggest that the current low population size
52 243 is due to unsuccessful settlement and/or severe predation by benthic predators
53 244 during the first months of life. One of the factors that influences the settlement
54 245 success is the wind direction and force during the pelagic larval phase, which
55 246 for *Spisula* lasts one month (Cardoso et al., 2007). The resulting hydrographic
56 247 patterns determine where the postlarval stage ends up, so where the spatfall
57 248 (settlement of shellfish larvae on or in the substrate) takes place (Belgrano

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4 249 et al., 1995; Armonies et al., 2001; Ellien et al., 2004). If spatfall takes place in
5 250 a favourable environment, a new *Spisula* bank may be formed. Craeymeersch
6 251 and Perdon (2006) tried to link data on wind direction and wind force to the
7 252 reproduction success of North Sea *Spisula subtruncata*, but did not find a good
8 253 correlation.

9
10 254 During the life cycle of bivalves, many other factors play a role as well. The
11 255 presence, or rather absence, of dense banks of adult specimens in the neigh-
12 256 bourhood may be a limiting factor, as was found for *Mya truncata* in the
13 257 Frisian Front (Amaro et al., 2003). *Macoma balthica* in the adjacent Wadden
14 258 Sea, has been hit by climate change that led to a decrease in reproductive
15 259 success, due to a shortage of food for larvae and an increased predation by
16 260 shrimp after mild winters (Philippart et al., 2003; Strasser et al., 2003; Bos
17 261 et al., 2006). Climate change can also lead to adult mortality as a result of
18 262 thermal stress and poor physiological condition, as was observed for *Spisula*
19 263 *solidissima solidissima* (Weinberg, 2005).

20 264 We observed that successful spatfall of *Spisula* does not occur yearly, Fig. 6.
21 265 The last successful recruitment in the Voordelta occurred in 1995. Along the
22 266 Zuid-Holland coast, recruitment in 1996 was followed by a smaller recruitment
23 267 in 2000. Recruitment in 2000 was better along the Noord-Holland and best
24 268 along the Wadden coasts. But 2000 was the last successful recruitment for
25 269 *Spisula* anywhere in The Netherlands.

26 270 Since *Spisula* is a short-lived species (approximately 4 years), the absence of
27 271 a successful recruitment after 2000 is disturbing. It might be that spatfall has
28 272 occurred in the meantime, but was preyed upon by the Brown shrimp *Cran-*
29 273 *gon crangon* (Beukema and Dekker, 2005). Data on shrimp densities along
30 274 the Dutch coast show no trend for the Holland coast and indeed an increasing
31 275 trend for the Wadden coast (Henk Heessen - IMARES, pers. com.). In recent
32 276 years spatfall of *Ensis americanus* has been very successful, despite shrimp
33 277 predation, but there is not enough knowledge on the biology of shellfish larvae
34 278 to explain possible differences. Based on Fig. 6 one might suspect a northern
35 279 shift in the distribution of *Spisula*. Notably the 0-year distribution in 2000
36 280 shows a distinct northern direction. The mean sea water temperature in the
37 281 North Sea has risen. Possibly *Spisula subtruncata* does not show a bathymetric
38 282 shift in response to warming, as does *Spisula solidissima solidissima* (Wein-
39 283 berg, 2005), but a northerly shift. Unfortunately, recent data on the presence
40 284 of *Spisula subtruncata* in German waters is lacking (Laursen and Essink, 2005;
41 285 ICES, 2005), but scoters off the Danish coast apparently still feed on *Spisula*
42 286 (Skov et al., 2008).

43 287 Since 2004, large adult *Spisula*-banks have been absent in the Dutch coastal
44 288 zone. *Spisula* does not suffer from reproductive failure (Cardoso et al., 2007)
45 289 and there might still be a viable, but low density population left. In com-
46 290 bination with correct meteorological and hydrodynamical circumstances, a
47 291 successful spatfall might re-occur, but there is no telling when, in the near
48 292 or distant future, this might happen. An interesting observation is that the
49 293 numbers of European Otter Clam *Lutraria lutraria* in Dutch coastal waters

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4 294 is increasing since the beginning of this century. The estimated biomass (in
5 295 fresh weight) for *Lutraria* in 2008 was approximately ten times higher than
6 296 for *Spisula* (Goudswaard et al., 2008). Their biomass should would need to
7 297 increase by 10-fold to reach the biomass of *Spisula* of the 1990s. Future studies
8 298 need to establish whether *Lutraria* can serve as an alternative food source for
9 299 wintering scoters.

300 5 Conclusion

301 High density *Spisula* banks were found along the Dutch coast in the 1990s.
302 Since 2001, *Spisula* recruitment has failed and its abundance has been declin-
303 ing sharply. Although shoreface nourishment volumes have been increasing
304 since that time, we cannot state that there is a causal relationship. It seems
305 that the decline was already on-going at the time of the nourishments.

306 The last good recruitment of *Spisula* in the Voordelta occurred in 1995, with-
307 out any nourishment at that time in this area. The first shoreface nourishment
308 of 1993 only had local effects and occurred in the north of the country, where
309 *Spisula* populations persisted for longest periods. The decline of *Spisula* ap-
310 peared to have happened first in the south, and last in the north of The
311 Netherlands, and does not seem to be correlated with the nourishments that
312 took place locally. At some locations a recovery of *Spisula* was observed af-
313 ter nourishment took place, such as Ameland 1998 and Terschelling 1993.
314 At other locations the shoreface nourishment seems to be the primary cause
315 for the decline, such as Noordwijk 1998, but assessed in a wider perspective,
316 the declining trend was present at more locations. Moreover, most shoreface
317 nourishments are applied in the morphodynamically active surf zone, whereas
318 *Spisula* is found further seaward. In conclusion, other causes, such as climate
319 change, fisheries, unsuccessful settlement or predation of spatfall are more
320 likely behind the decline of *Spisula* along the Dutch coast and nourishments
321 may have played only an additional role.

322 The numbers of Common Scoters have declined in recent years, as well. This
323 seems primarily the result of the declining availability of their main food
324 source, *Spisula*. Because we cannot link the decline of *Spisula* to the shoreface
325 nourishments, we do not think any direct or indirect effects of the shoreface
326 nourishments can be held responsible for the observed decline of the popula-
327 tion of Common Scoters in The Netherlands.

328 6 Acknowledgments

329 Our sincere thanks go to Elze Dijkman, Jenny Cremer and Alexander Bosma
330 (IMARES-Texel) for their GIS-analyses. We thank Johan Craeymeersch, Jack
331 Perdon and Joke Kesteloo-Hendrikse (IMARES-Yerseke) for providing data on
332 *Spisula*. This project was committed and supervised by Ilse Jonker, Ministry
333 of Transport, Public Works and Water Management, National Institute for
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1 **Figure 1.** Total number of adult *Spisula subtruncata* (solid line, left axis) and the nourished volume of sand (bars, right
2 axis) for the entire Dutch coast. Number of nourishments per year above the bars. Data courtesy of the National Institute
3 for Coastal and Marine Management..
4

5 **Figure 2.** Winter maxima of abundance of Common Scoter (*Melanitta nigra*) along the entire Dutch coast. Data courtesy of
6 the National Institute for Coastal and Marine Management / RIKZ, IMARES, NIOZ and Dutch Seabird Group.
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8 **Figure 3.** Locations of the shoreface nourishments along the Dutch Coast. Large labels denote the eight nourishment
9 locations discussed in the text and small labels (underlined) denote regional names used in the text. NAP is Dutch
10 Ordnance Level.
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12 **Figure 4.** Biomass of adult *Spisula* combined with nourished volumes in four sections of the Dutch coast. Numbers denote
13 nourished volumes in Mm^3 . The surface area of the circles scales with the size of the volume or biomass. .
14

15 **Figure 5.** Estimated *Spisula* density for 0-year and adult age classes in nourishment locations. A white, thin bar represents
16 the year of the shoreface nourishment, 'n.d.' means 'no data'. The Terschelling nourishment took place in 1993 (off scale).
17 These eight examples are scattered over the total time-frame of this study and over a large part of the Dutch coast.
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19 **Figure 6.** Biomass of 0-year and adult age classes of *Spisula* in four main sections of the Dutch coast. Numbers given
20 denote biomass of fresh weight of adults in ktons (10^6 kg).
21

22 **Table 1.** Shoreface nourishments in The Netherlands. Data from Roelse (2002), Steijn (2005) and Ministry of
23 Transport, Public Works and Water Management. Beach Pole denotes the section along the beach where the nourishment
24 took place. NAP is Dutch Ordnance Level.
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26 **Table 2.** *Spisula* abundance at nourishment locations with area in hectares, as calculated from interpolated data.
27 Nourishment locations that were used in multiple years and overlap almost completely were combined to one (n.d. – no
28 data).
29

30 **Table 3.** *Spisula* abundance at extended (down to -20 m depth contour if possible) nourishment locations, with area in
31 hectares, as calculated from interpolated data (n.d. – no data).
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Figure 1

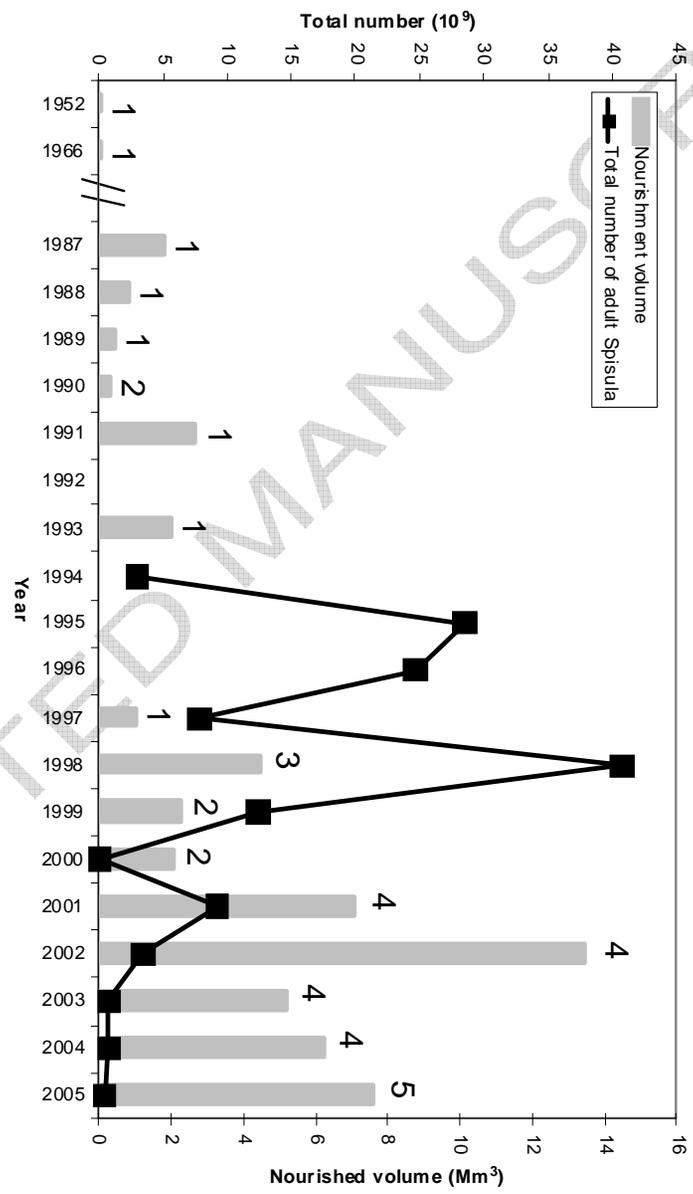


Figure 2

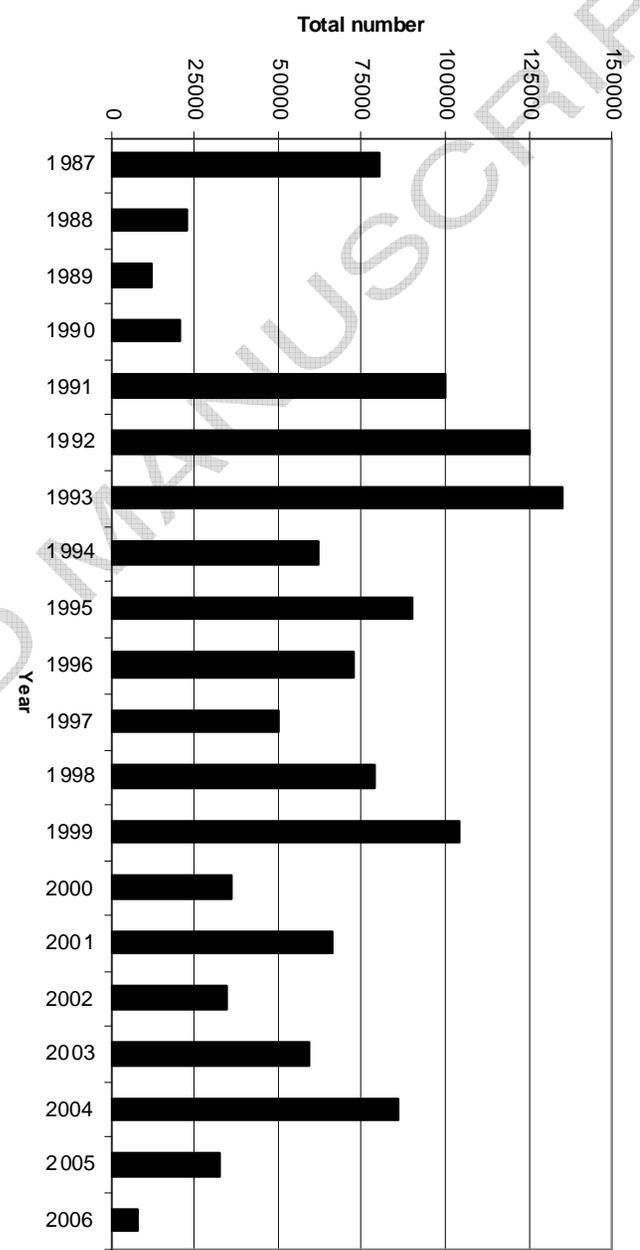


Figure 3

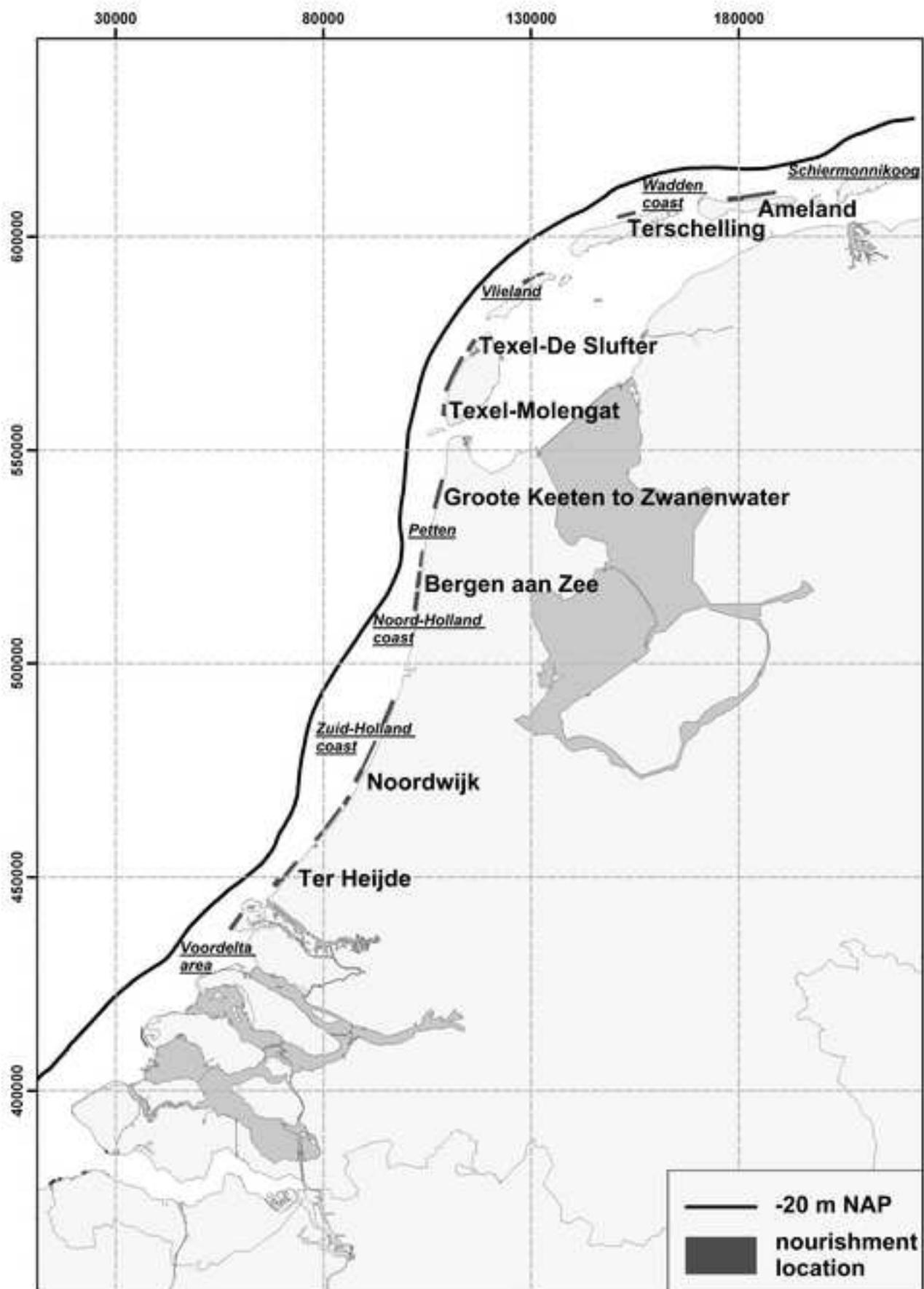
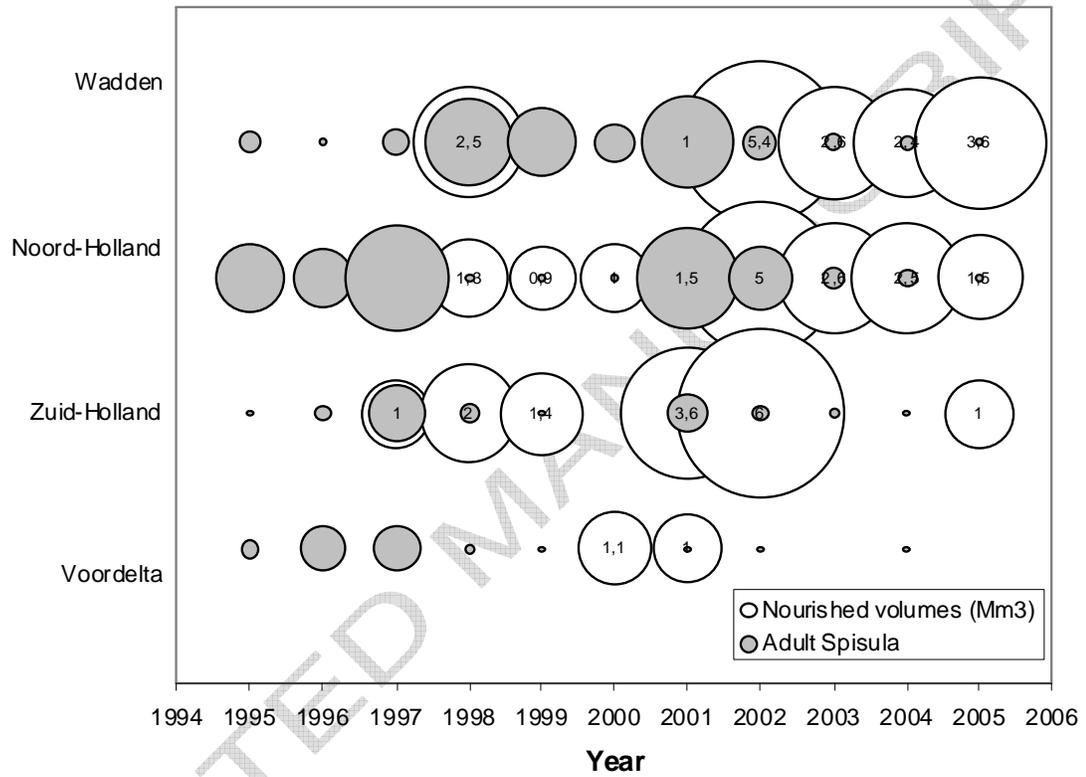
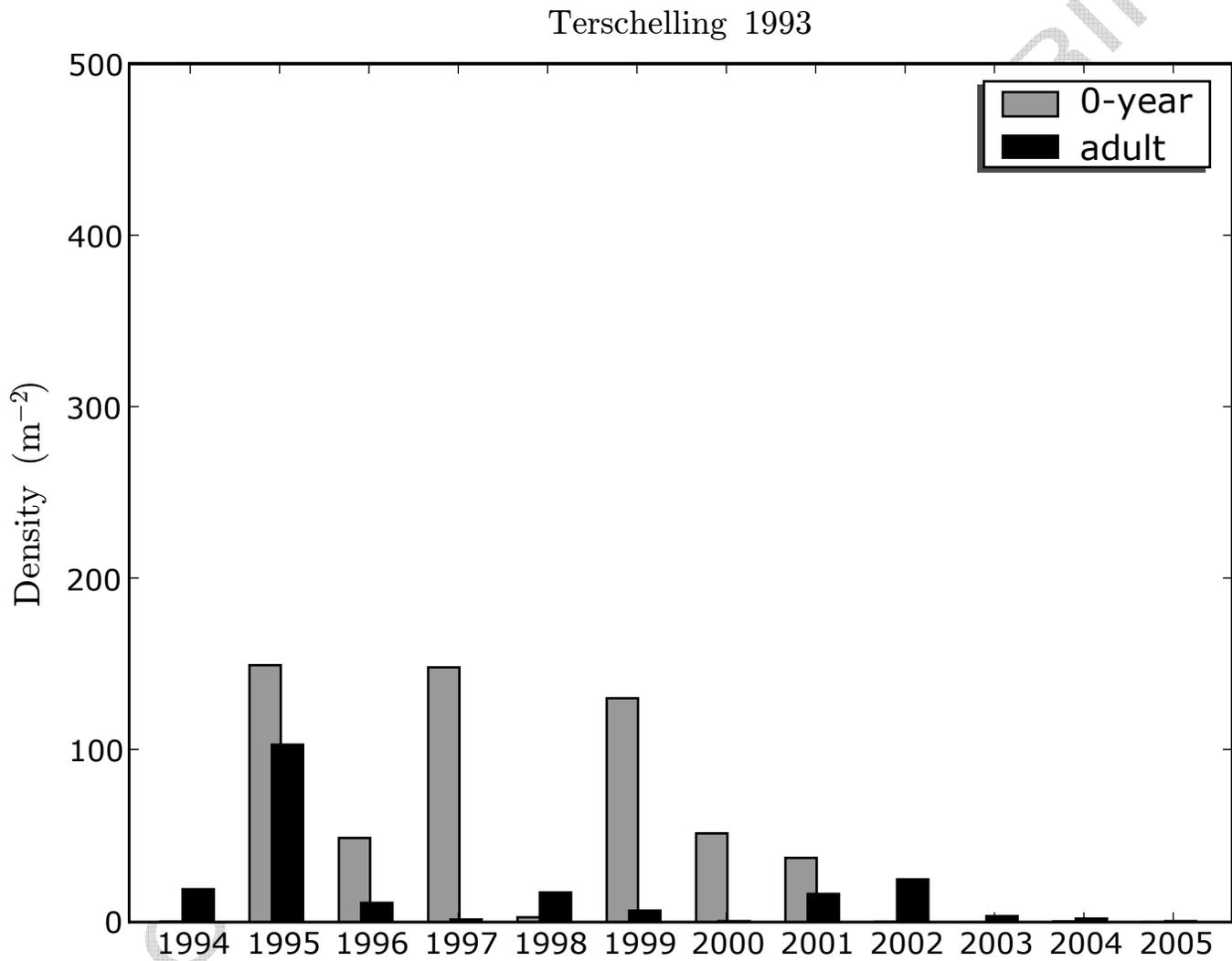
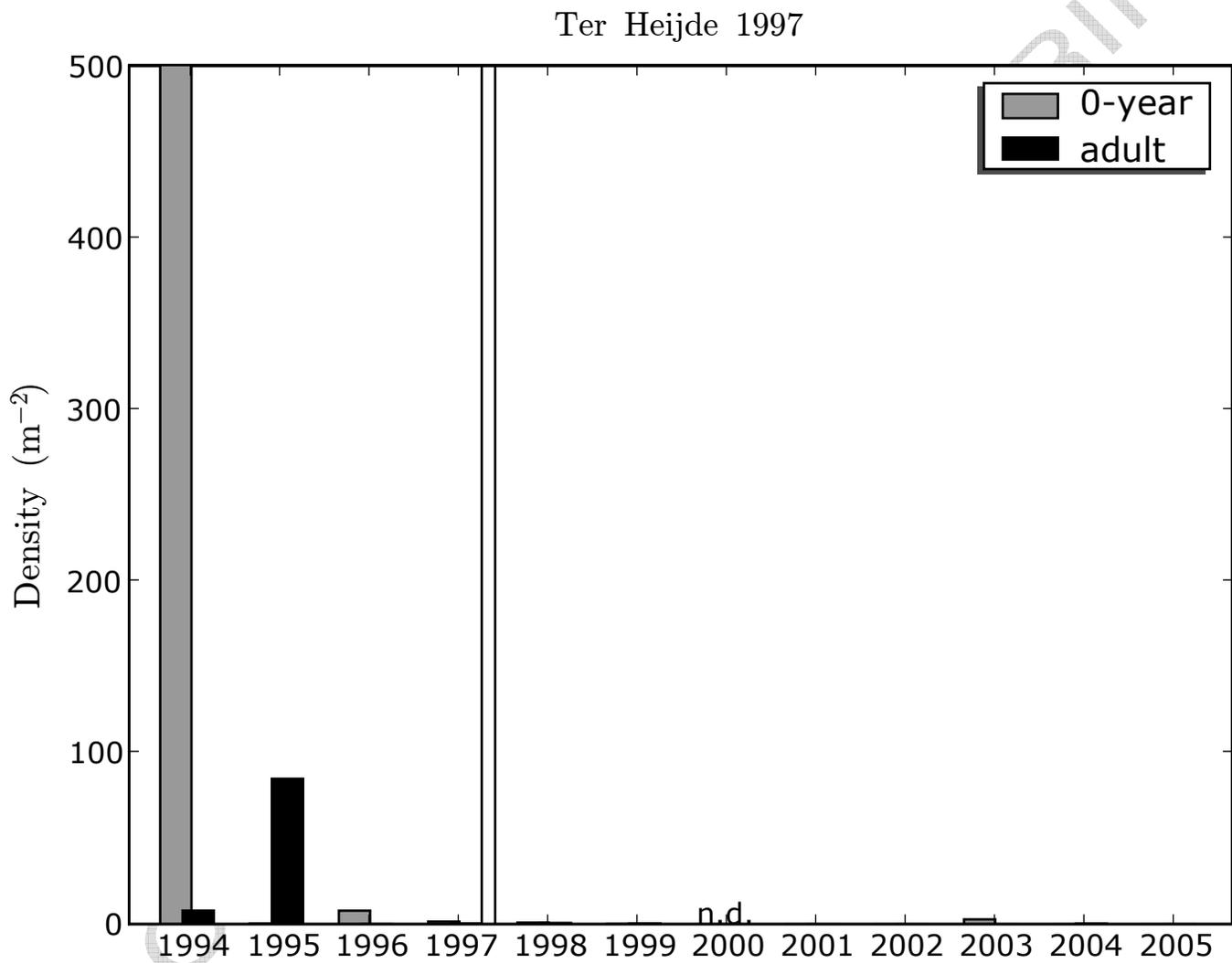
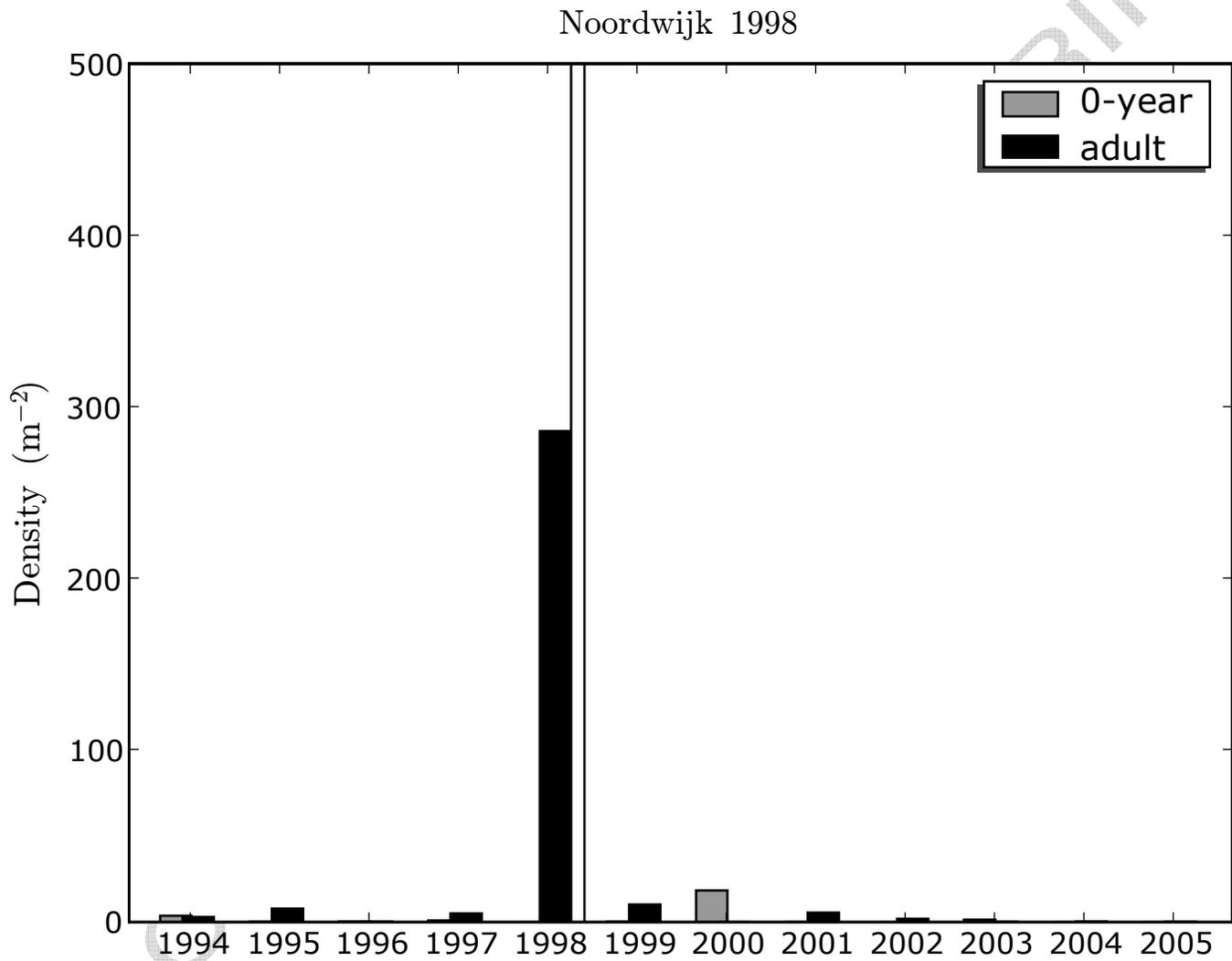


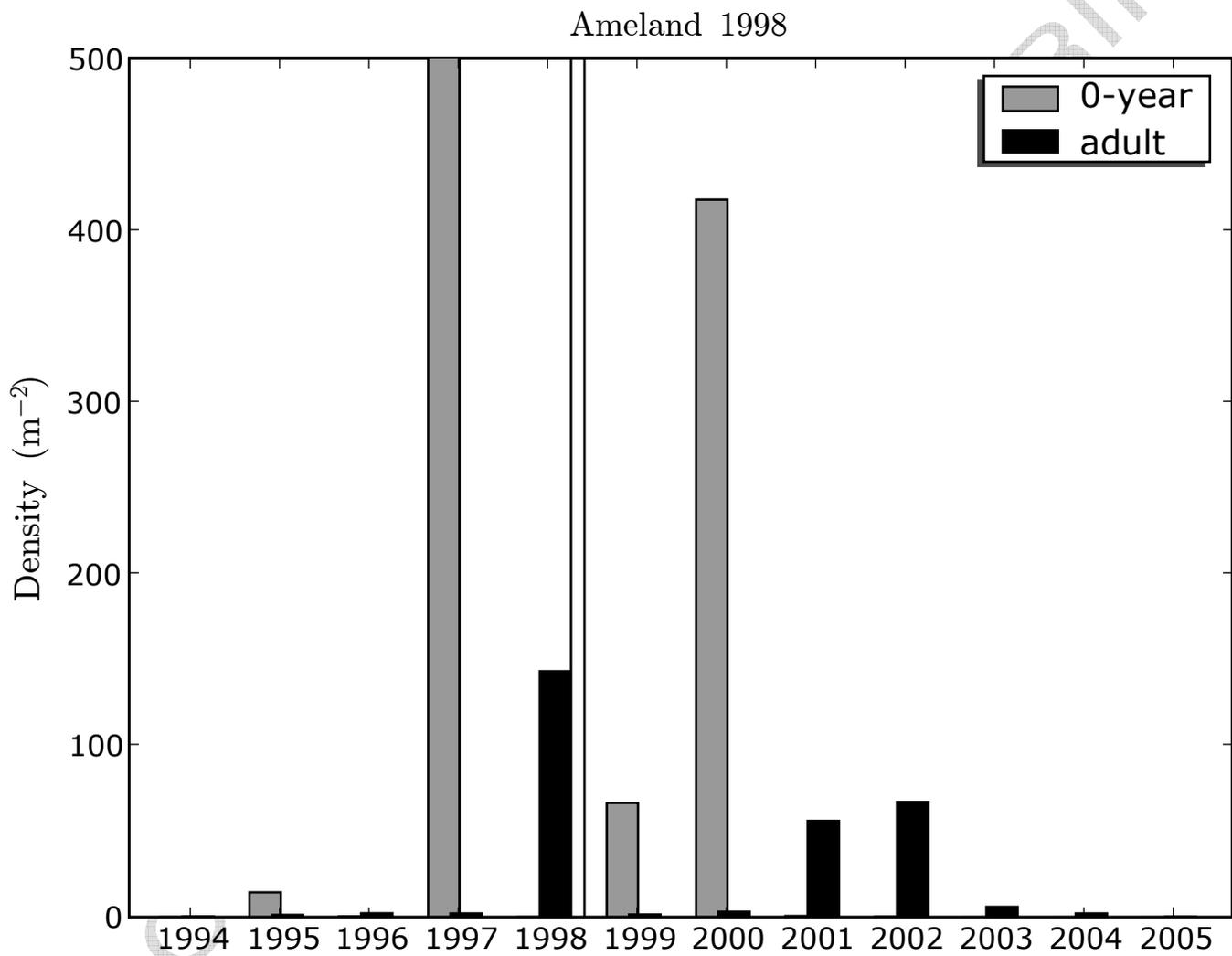
Figure 4

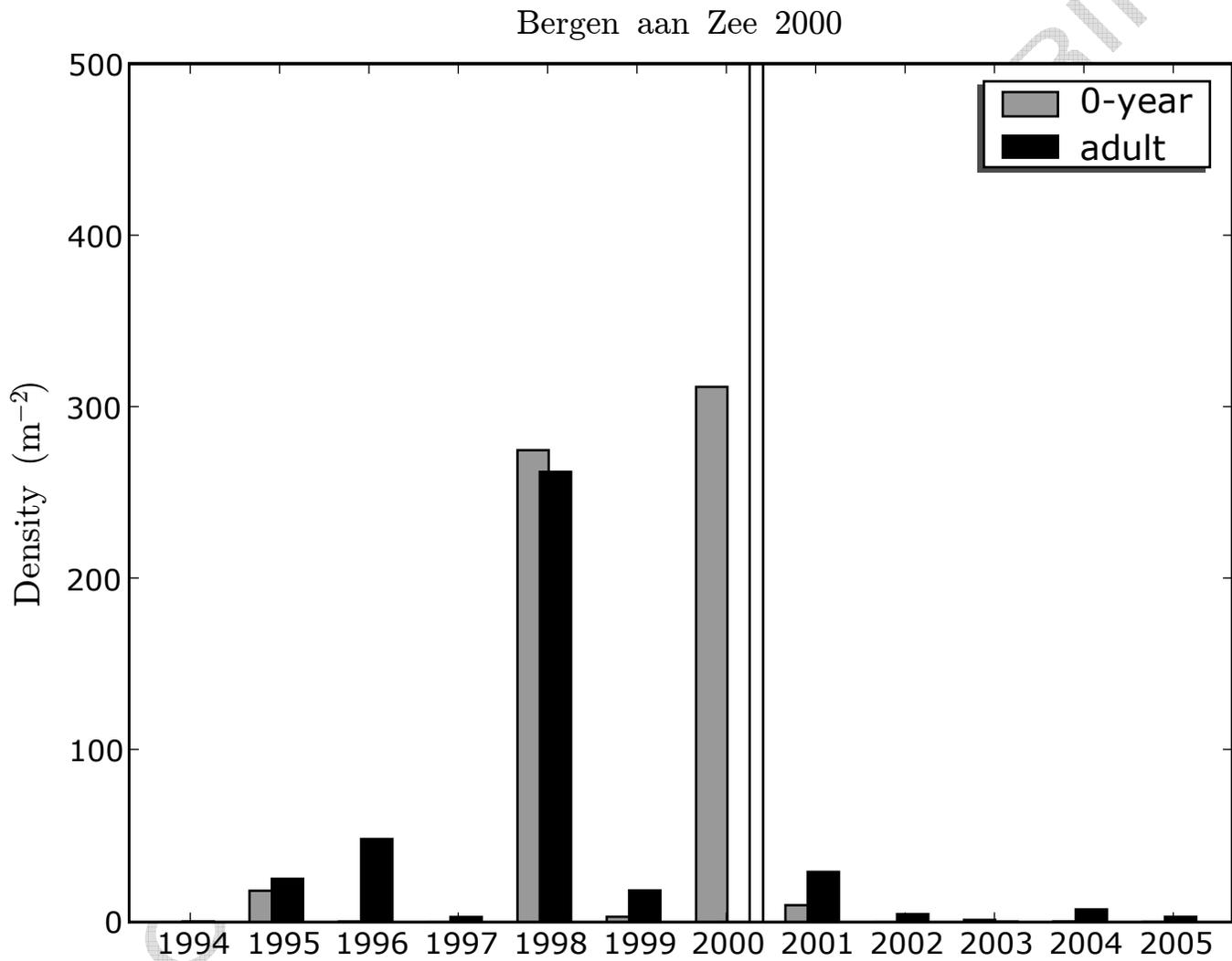


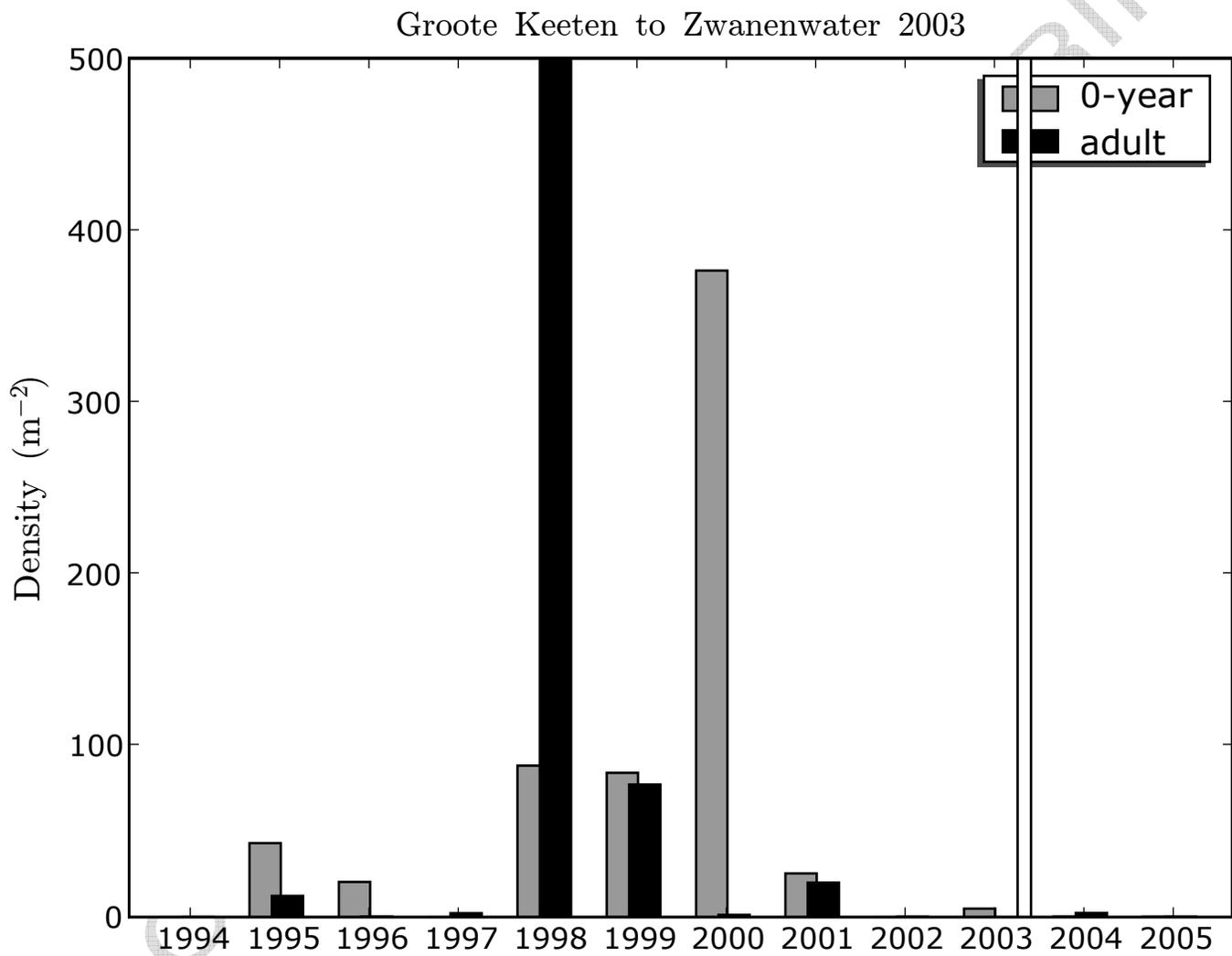


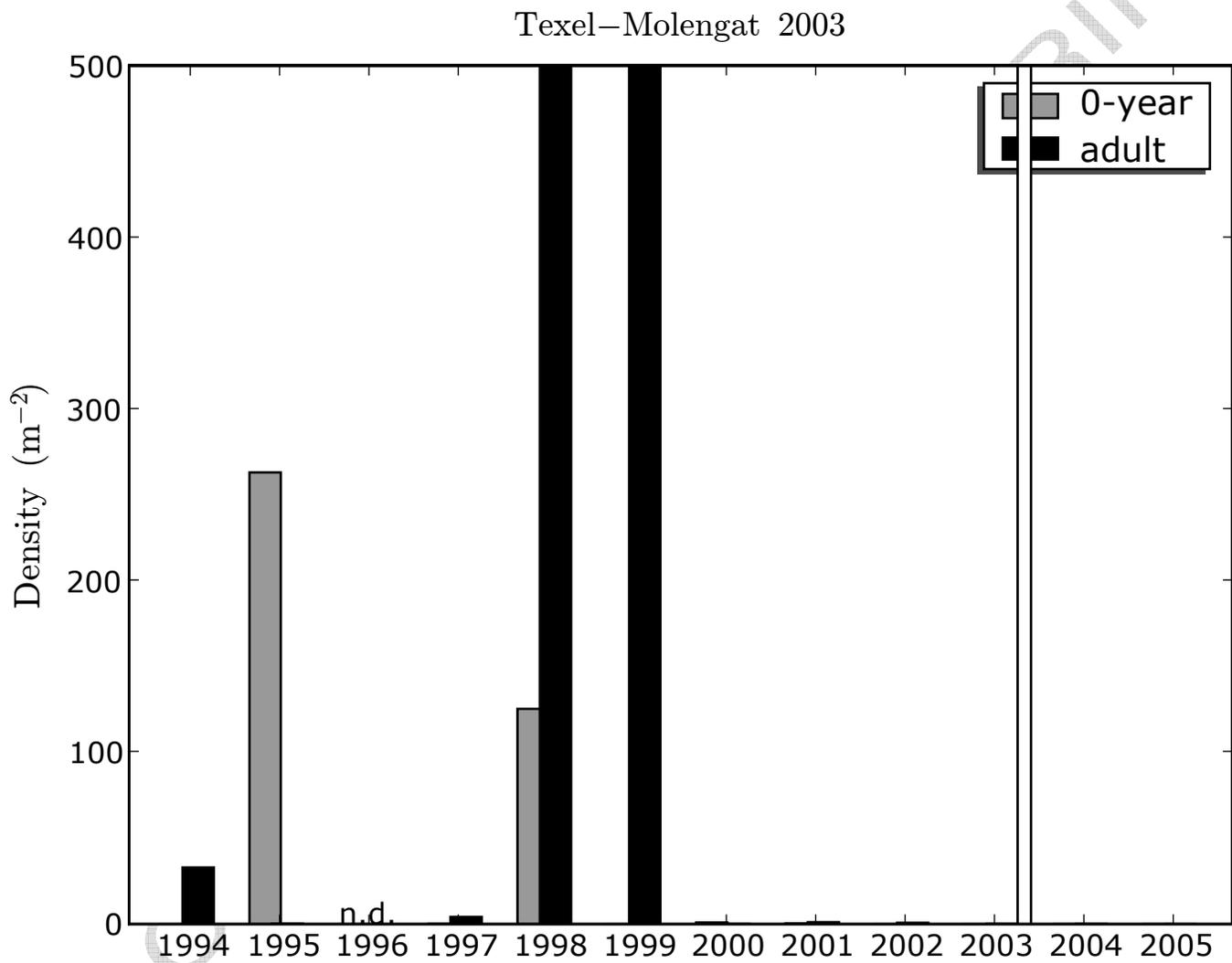












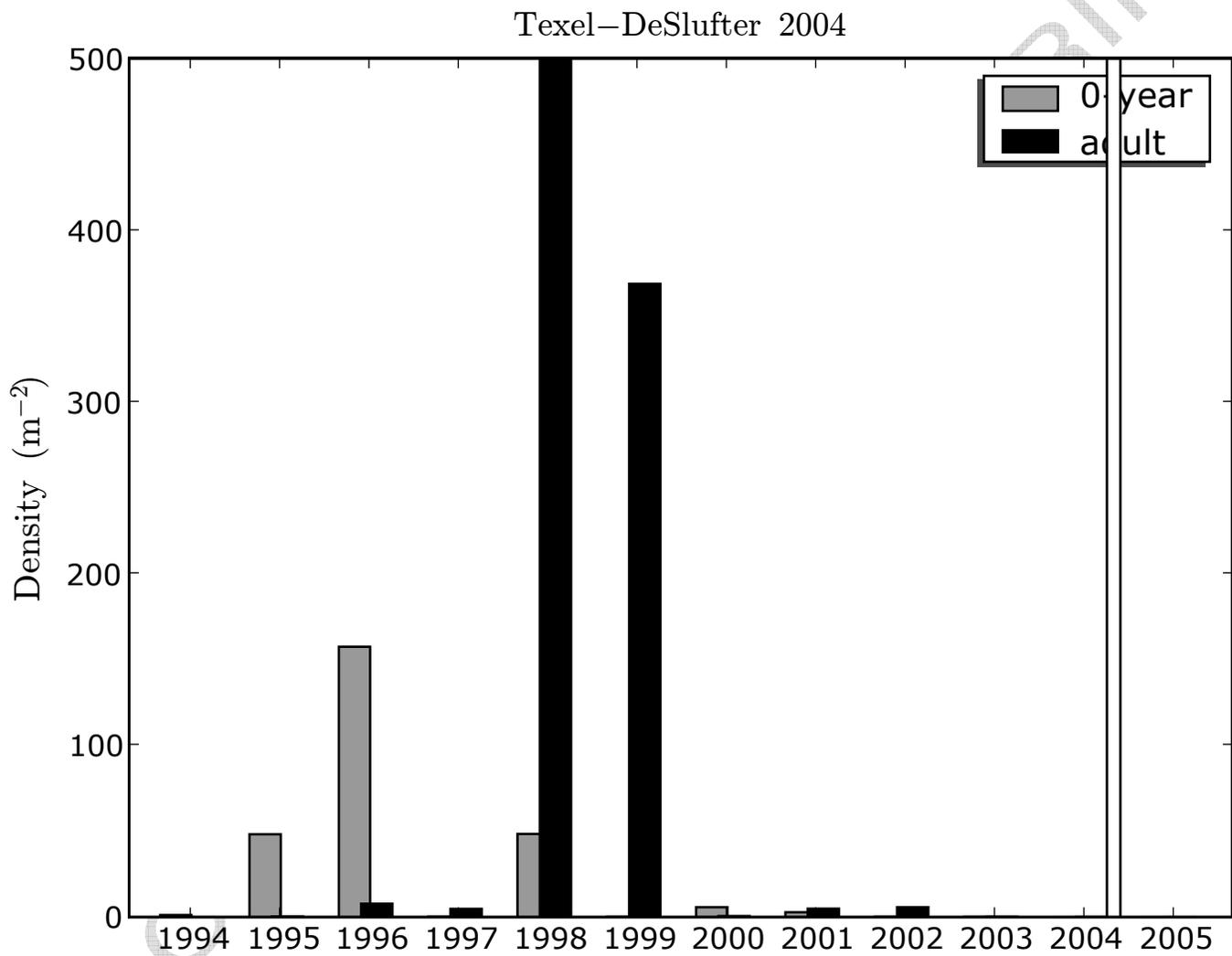
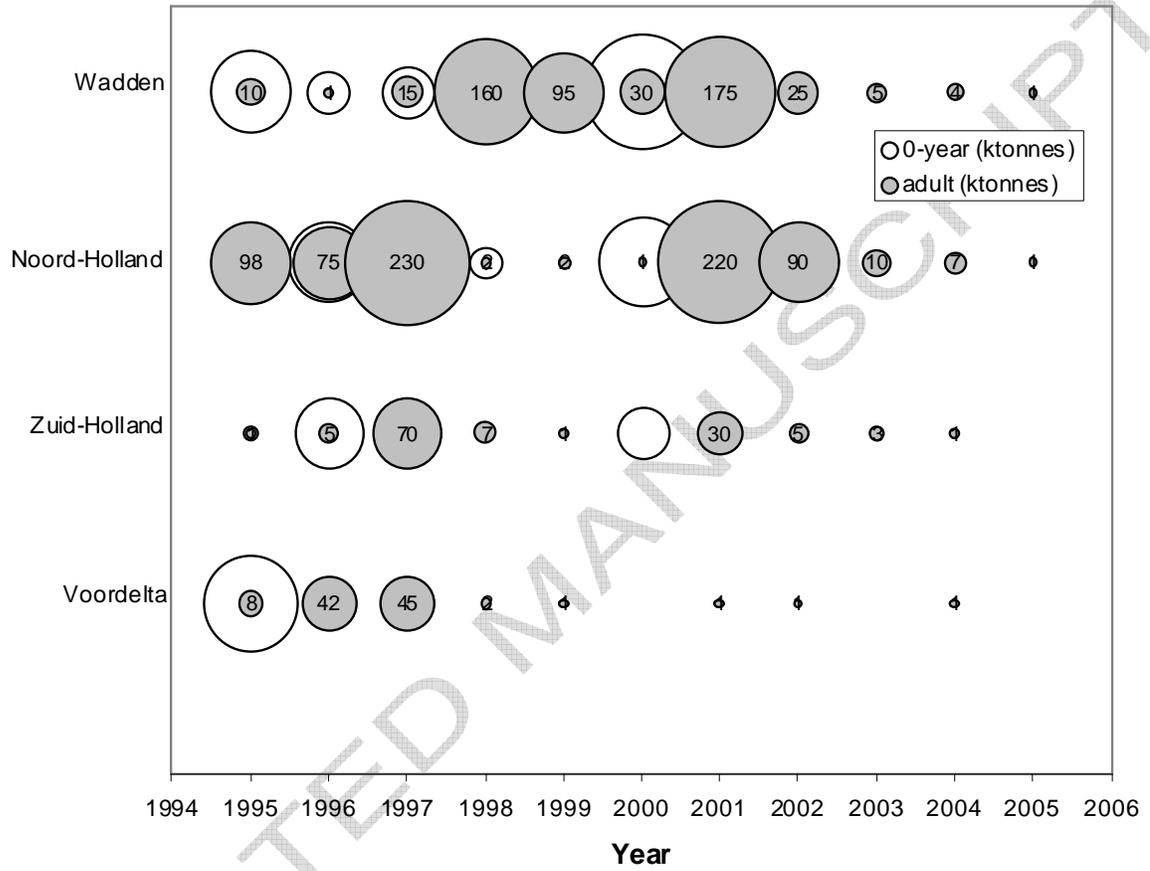


Figure 6



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Nourishment location	Beach Pole	Period (month year)	Size (Mm ³)	Type	Depth (m NAP)
1 Cadzand west	13.3-14.3	Oct-Nov 1990	0.32	Channel slope + beach	to -8
2 Cadzand west	13.3-14.3	1988	0.85	Channel slope + beach	to -8
3 Tienhonderdpolder	10.4-11.1	Nov-Dec 1990		unknown	-5 to -7
4 Groede	5.3-6.02	Sep-Nov 1989	0.44	Channel slope + beach	to -8
5 Vlissingen 1952	34-34.4	Apr-Nov 1952	0.05	Channel slope	-2 to -3
6 Vlissingen 1966	34-34.4	Jan-Mar 1966	0.032	Channel slope	-2 to -5
8 Kop van Schouwen	13.2-15.6	apr-jun 1987	1.83	Channel slope + beach	to -10
9 Kop van Schouwen	13.2-15.6	1991	2.67	Channel slope + beach	to -10
10 Maasvlakte	6.41-10.54	Aug-oct 2000	1.1	Shoreface	-4 to -8
11 Maasvlakte	6-10.02	Nov 2001-Jan 2002	1	Shoreface	-5 to -7
12 Ter Heijde	113.15-114.85	Aug-Nov 1997	1.03	Shoreface	-5 to -8
13 Monster	108-113	Jan-Dec 2005	1	Shoreface	-5 to -7
14 Kijkduin - Ter Heijde	107.4-112.5	Mar-Nov 2001	3.58	Shoreface	-5 to -7
15 Scheveningen	97.73-100.5	Feb-Jun 1999	1.43	Shoreface	-5 to -8
16 Wassenaar	91-97	Feb-Dec 2002	3	Shoreface	-5 to -7
17 Katwijk	87.5-89.5	Sep 1998-Feb 1999	0.75	Shoreface	-5 to -7
18 Noordwijk	80.5-83.5	Jan-Apr 1998	1.27	Shoreface	-5 to -7
19 Noordwijkerhout	73-80	Apr-Dec 2002	3	Shoreface	-5 to -7
20 Zandvoort zuid	65.75-67.75	Oct-Dec 2004	0.9	Shoreface	-5 to -7
21 Zandvoort noord	62.75-65.75	Nov 2004 - Jan 2005		Shoreface	-5 to -7
22 Egmond	36.9-39.1	Jun-Sep 1999	0.88	Shoreface	-5 to -8
23 Egmond	36.2-40.2	Jun-Nov 2004	1.6	Shoreface	-5 to -7
24 Bergen aan Zee	32.25-34.25	Apr-Aug 2000	1	Shoreface	-5 to -7
25 Bergen aan Zee	31.5-35	Jan-Dec 2005	1.5	Shoreface	-5 to -7
26 Camperduin	26.5-30	Jun-Oct 2002	2	Shoreface	-5 to -7
27 Grootte Keeten - Zwanenwater	10-16	Feb-May 2003	2.57	Shoreface	-5 to -7
28 Callantsoog	11.08-14.01	Jun-Oct 2001	1.5	Shoreface	-3 to -6
29 Grootte Keeten	9.13-9.43	Aug 2003	0.012	Shoreface	-5 to -7
30 Texel Molengat	9-11.48	Feb-Aug 2003	1.2	Channel slope	-3 to -6
31 Texel midden	14-17.5	Jan-Dec 2005	2.6	Shoreface	-5 to -7
32 Texel De Koog	17-23	Mar-Nov 2002	5.4	Shoreface	-6 to -9
33 Texel De Slufter	25.1-27.9	Jun-Sep 2004	2.4	Shoreface	-5 to -7
34 Vlieland midden	46.2-48.5	Apr-Aug 2001	1	Shoreface	-5 to -6
35 Vlieland oost	48.8-50	Jan-Dec 2005	1	Shoreface	-5 to -7
36 Terschelling midden	13.7-18.1	Apr-Nov 1993	2	Shoreface	-5 to -7
37 Ameland midden	9.4-13.7	Jul-Nov 2003	1.43	Shoreface	-3 to -5
38 Ameland oost	13-21	Apr-Sep 1998	2.5	Shoreface	-5 to -7

		ad.	0.1	0.3	0	0.4	0.1	0.3	0	0	0	0	0
Vlieland oost	30.4	0-yr	0	2	n.d.	0	0	0	0	0	n.d.	n.d.	n.d.
		ad.	0	0	n.d.	0	0	0	0	0	n.d.	n.d.	n.d.
Terschelling midden	212.5	0-yr	0.3	150.1	49.2	148.8	2.9	130.8	51.9	37.6	0.1	0	0.5
		ad.	19.3	103.7	11.3	1.6	17.3	6.8	0.7	16.6	25.1	3.5	2.2
Ameland midden	231.6	0-yr	0.1	18.2	13.8	341.2	0.2	493.3	14.6	2	0	0	0
		ad.	71.3	4.4	4	8.5	35.3	0.3	0.7	85.1	4.7	2.2	0.2
Ameland oost	368.9	0-yr	0	14.5	0.5	582.4	0	66.8	418.7	0.7	0.2	0	0
		ad.	0.4	1.3	2.3	2.2	143.5	1.6	3.2	56.2	67.3	6	2.2

ACCEPTED MANUSCRIPT

Table 3

ACCEPTED MANUSCRIPT

Nourishment location	ha	age	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Maasvlakte	2813.9	0 yr.	15.9	97.3	36.5	0.2	0	1.2	0	0.1	0	1.4	0.6	0
		ad.	0.2	3.9	42.8	35.9	0.9	0	0	0.1	0.1	0	0.3	0.4
Ter Heijde	1060.8	0 yr.	242.4	0.2	9.7	0.5	0.4	0	0.1	0	0.4	1.2	1.1	0.1
		ad.	2.5	12.3	0.2	11.8	5.5	0.5	0	0	0	0	0.7	0.8
Monster	3040.4	0 yr.	0	0	24.5	1.9	11.9	0.7	2.1	0.4	1.5	4.3	2.5	0.3
		ad.	0	0.1	0.1	2.8	6.7	0.8	0.1	0.3	0	0.5	1.2	1.7
Kijkduin-Ter Heijde	3239.4	0 yr.	1.2	0.8	20.4	2.2	12.6	0.6	2.1	0.4	1.5	4.3	2.6	0.3
		ad.	1.1	0.1	0.2	2.8	7	0.8	0.1	0.3	0	0.6	1.3	1.7
Scheveningen	2315.6	0 yr.	0.2	1.7	8.8	0.1	1	0	0.3	0.2	0.1	0.2	0	0.1
		ad.	0	0	1.4	7.5	2.4	0	0.1	0	0.1	0.3	0.2	0.1
Wassenaar	5604.9	0 yr.	0	2.5	60.3	0.2	3.7	0.1	0.1	0.3	0.6	1	0	0.2
		ad.	0.1	0.2	4.8	14.5	5.2	0.2	0	0.1	0.1	0.3	0.4	0.1
Katwijk	2705	0 yr.	0.1	13.4	1.4	0.3	0.8	0	0	0.3	0	0	0	0
		ad.	18.3	95.1	123.5	1.8	18.9	0.3	0.3	12.3	19.8	0.7	0.7	0.7
Noordwijk	4236.9	0 yr.	0.2	0.2	2	0.5	0	0	7.5	1.2	0	0.2	0.2	0.2
		ad.	0.1	2.3	0.1	1.2	13.7	0.5	0	0.6	1.6	0.1	0.2	0
Noordwijkerhout	10863.2	0 yr.	0.1	0.1	2.8	0	0	0	2.8	4.8	0	0.3	0	0
		ad.	0	0.1	0.2	1.2	0.3	0.2	0	0.7	0.7	0.2	0.1	0
Zandvoort zuid	4862.6	0 yr.	0.1	0	1147.6	0	0.1	0	1.5	0.5	0	0.1	0	0
		ad.	0	0	0.2	2.3	0	0	0	0.8	0.2	0	0	0
Zandvoort noord	3976.7	0 yr.	0	0	4426.4	0	0.1	0	0.6	0.1	0	0.1	0	0
		ad.	0	0	0	9.5	0.2	0	0	0.6	0.4	0	0	0
Egmond	2885.1	0 yr.	2.8	6.4	1.1	0	1.8	1.7	59.3	3.1	0.1	2.3	0.9	0
		ad.	1	21.5	16.4	16.8	0	0.7	0.1	10.2	2	0.7	2.2	1.2
Bergen aan Zee	997.3	0 yr.	0	109.1	0.1	0	33.6	0.3	451.1	3.2	0	11	0.2	0.1
		ad.	3.1	348.8	279.7	27	106.9	1.7	0	78.1	10	5.1	4.5	3.6
Bergen aan Zee	1978.7	0 yr.	0	81.5	0.1	0	35.3	0.3	477	3	0	12.7	0.3	0.1
		ad.	1.8	352	240.2	28.3	108	1.9	0	111.4	38.8	7.7	5.4	3.4
Camperduin	1634.1	0 yr.	38.9	152.8	30.5	0	13.7	0.4	682.5	2.1	0.9	45	0.1	0.1
		ad.	13.6	271.9	247.4	29.6	45.8	1.4	0.1	42.6	12.8	13.7	17	1.6
Groote Keeten-Zwanewater	4997.1	0 yr.	0.5	2.5	25.2	0	6.4	6.7	24.3	2	0	0.3	0	0
		ad.	0.5	1.3	0.3	2.7	46	4.9	0.1	2.5	0.1	0	0.3	0.1
Callantsoog	2729.4	0 yr.	0.7	1.3	10.7	0	4.4	4.5	16.4	1.4	0	0.2	0	0
		ad.	0.7	1	0	1.8	26.3	2.9	0	1.9	0.2	0	0.2	0.1
Groote Keeten	410.8	0 yr.	0.3	0.2	132.5	0	1.1	0.9	3.7	0.4	0	0	0	0
		ad.	0.3	0.5	0.1	5.4	3.3	0.4	0	4	0.1	0	0	0
Texel Molengat	1600.7	0 yr.	0	347.6	57.7	0.5	45.9	0	16.7	9.7	0	0	0	0
		ad.	2.3	0.6	1.7	14.1	841.1	308.6	1.1	5.6	1.9	0.3	0.2	0
Texel midden	1610	0 yr.	0	284.7	118.8	0.5	62.2	0	20.7	7.6	0	0	0	0
		ad.	3.7	0.9	3.2	12.3	749.3	317.8	0.8	4.3	1.9	0.3	0.2	0
Texel De Koog	3906.6	0 yr.	0	0.4	0.2	0	0.7	0	4.7	0.5	0	0.1	0	0
		ad.	0	0	0	0.1	3.2	1	0	0.2	0.1	0.1	0	0
Texel De Slufter	2155.2	0 yr.	0.1	3.6	10.9	0	5.2	0	5.9	0.5	0	0.1	0	0
		ad.	0.2	0.1	0.7	45.2	124.1	41.6	0.1	1.2	1.6	0.1	0	0
Vlieland midden	2601.9	0 yr.	0	4.5	1.4	0	0	0	0	0	0	0	0	0
		ad.	0	0.1	0	0	0	0.1	0	0	0	0	0	0
Vlieland oost	1500.1	0 yr.	0	0	2.6	0	0	0	0	0	0	0	0	0
		ad.	0	0	0	0	0	0	0	0	0	0	0	0
Terschelling midden	2794.5	0 yr.	0.4	20.5	41	136.3	1.2	20.7	23.5	57.5	0.1	0	0.4	0
		ad.	14.5	33.8	2.4	0.4	8.1	1.3	0.1	6.1	16	0.5	0.8	0.3
Ameland-midden	2430.1	0 yr.	1.2	1253.9	10.4	723.7	0.3	68.4	25.9	12	0	0.5	0	0.6
		ad.	45.2	196.4	75	9.3	9	0.2	0.1	137.6	18	5.5	3.2	1
Ameland oost	4936.2	0 yr.	2.5	855.2	2.2	271.8	0.3	13.5	77.2	0.5	0.6	0	0.1	0
		ad.	0	0.1	0.2	1.8	0.4	0.1	0	0.2	0.2	0.1	0	0