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Buried Alive: Effects of Beach Nourishment on the Infauna of an Erosive Shore in the North Sea

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With 13 Figures and 8 Tables

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Abstract

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Artificial beach nourishment as a 'soft' means of protection has become the preferred method to combat shoreline erosion. However, the beach infauna may be affected by such a disturbance. Up to 3 m of sand have been piled upon beaches, followed by enhanced sediment dynamics. The impact of two nourishment operations of different magnitude (159,000 and 351,000 m^3/2 km beach line) on meio- and macrofauna across a shore on the island of Sylt (North Sea) has been studied between 1999 and 2001. No significant effect on meiofauna was noticed after the smaller operation in 1999, while a decreased copepod abundance in the shallow subtidal and a reduced polychaete species density at mid shore occurred four months after the larger nourishment. In the macrofauna, a short-term reduction of the two species dominating the shallow subtidal, the isopod *Eurydice pulchra* and the polychaete *Scolelepis squamata*, was noticed in 1999. A stronger and more lasting negative effect was caused by the larger operation in 2000. Macrofaunal abundance and species density in the deeper subtidal zone were lower than at the reference site even nine months after the nourishment. However, these infaunal responses to both beach nourishments are not considered as dramatic when compared to natural changes along the shore and between years. From an ecological perspective, sand replenishments may be regarded as an acceptable method for coastal protection, provided that intervals of at least three years are kept between successive operations at a given site.

Introduction

Coastal erosion threatens to become an unrelenting problem due to the combined effects of coastal development and rising sea level (LEATHERMAN 1987; CHARLIER & DE MEYER 1995; LOZÁN et al. 2001). To combat coastal erosion, the traditional approach has been the construction of groynes, breakwaters, sea walls, the placement of tetrapods etc. These 'hard' means of protection have frequently been found unsatisfactory due to hazards to beach users, lack of aesthetic appeal, occasionally enhanced erosion further downshore, and high costs coupled with limited effectiveness (WALTON & SENSABAUGH 1979; REILLY & BELLIS 1983; PILKEY & WRIGHT 1989; COOPER 1998). In view of these limitations, sand

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replenishment as a 'soft' protection has now become the preferred method for dealing with shoreline erosion (REILLY & BELLIS 1983; NELSON & PULLEN 1985; NELSON 1993; NORDSTROM 2000). The essential effect of this method is to restore the beach to its former condition and to allow it to repeat an earlier sequence of erosion.

The use of sand replenishment has rapidly increased in the last decades and increasing amounts of replenished material per project have been applied (VALVERDE et al. 1999). This raises challenging questions about the consequences of these large-scale disturbances for the beach ecosystem. How do effects vary with the amount of replenished sand and the spatial scale of the operation? The immediate impact in many cases is that the benthos is buried beneath a massive layer of 1-3 m sand at the upper shore (RAKOCINSKI et al. 1996). After the operation, hydrodynamics gradually restore the shore's original morphology, concurrent with an increasing sediment mobility (BROWN & MCLACHLAN 1990). This may also affect the infauna seaward of the upper shore. Studies on ecological consequences of beach nourishment have rarely found their way into pre-reviewed literature (NELSON 1993), and most of them deal with macrofauna only, while equivalent studies on meiofauna are scarce. Due to a focus on fore- and inshore macrofauna, possible effects on the adjacent subtidal communities have rarely been studied (e.g. ESSINK 1997).

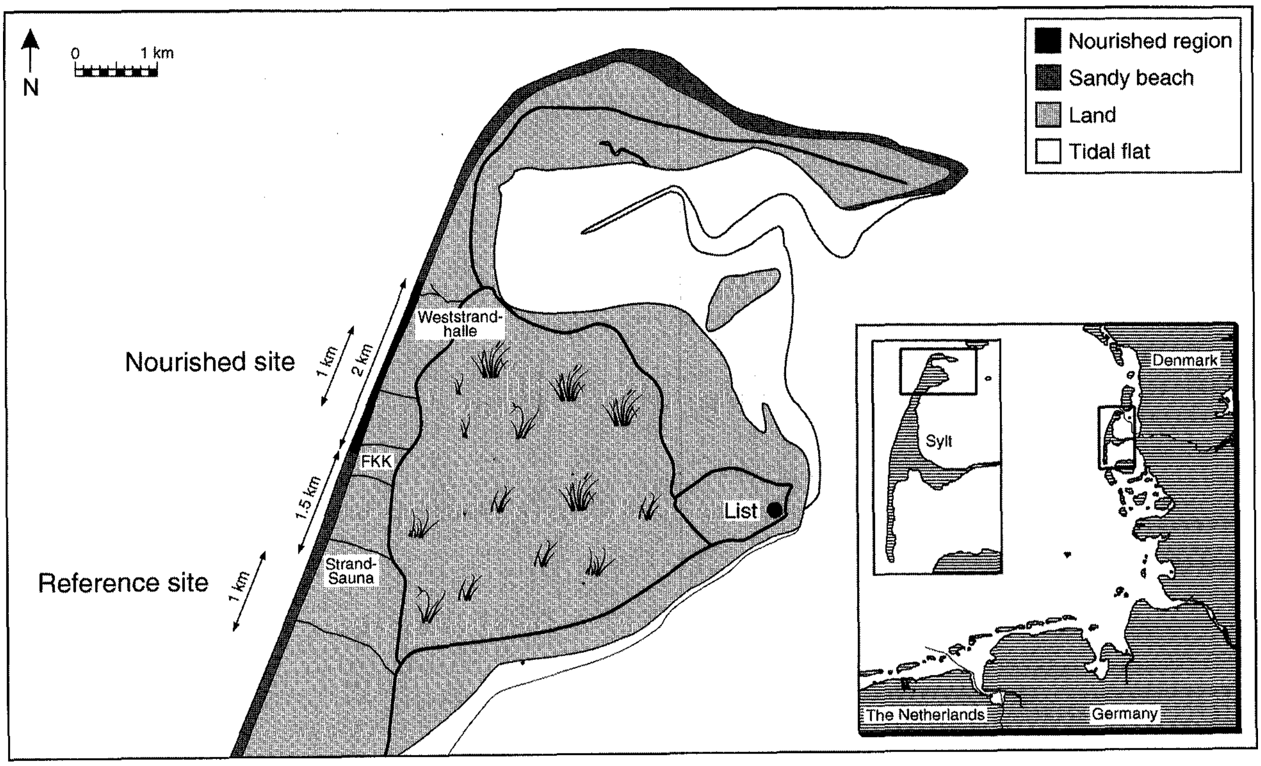
The growing scale of beach nourishments and the paucity of information on its ecological effects induced us to study the consequences for both meio- and macrofauna from the intertidal towards the subtidal shoaling zone. On the island of Sylt (Germany), two operations differing in the amount of sand applied were investigated: at a beach length of 2 km 159,000 m^3 of sand were deposited in 1999 and a further amount of 351,000 m^3 was added to the same site in 2000. A nearby undisturbed beach was simultaneously studied for comparison and to assess seasonal effects. Reduced infaunal abundances and species densities at the nourished site after the operation compared to the reference site are defined as negative effects, provided that no lower values already occurred before the nourishment. Recommendations for beach nourishments are given, especially on how to keep their ecological impact low. Generally, the impact is assumed to be smaller on meiofauna than on macrofauna, as meiofauna seems to be better adapted to mobile shore sediments than most macrofauna (MCINTYRE 1971; MCLACHLAN et al. 1984; MENN 2002). Effects on the adjacent subtidal may increase with the amount of sand supplied to the backshore and beachface.

Material and Methods

Study Site

The studied shore is located at the exposed western side of the barrier island of Sylt (Germany) in the eastern North Sea (Fig. 1). The average water temperature of this cold-temperate region is 4°C in winter and 15°C in summer. During the study period, surf water salinity was in the range of 27-33 PSU and interstitial water had 27-29 PSU. Tides are semidiurnal, with a mean range of 1.8 m and little difference between neaps and springs.

Two sites at the northern part of Sylt, each 1 km in shore length, were studied. The nourished site is located in a



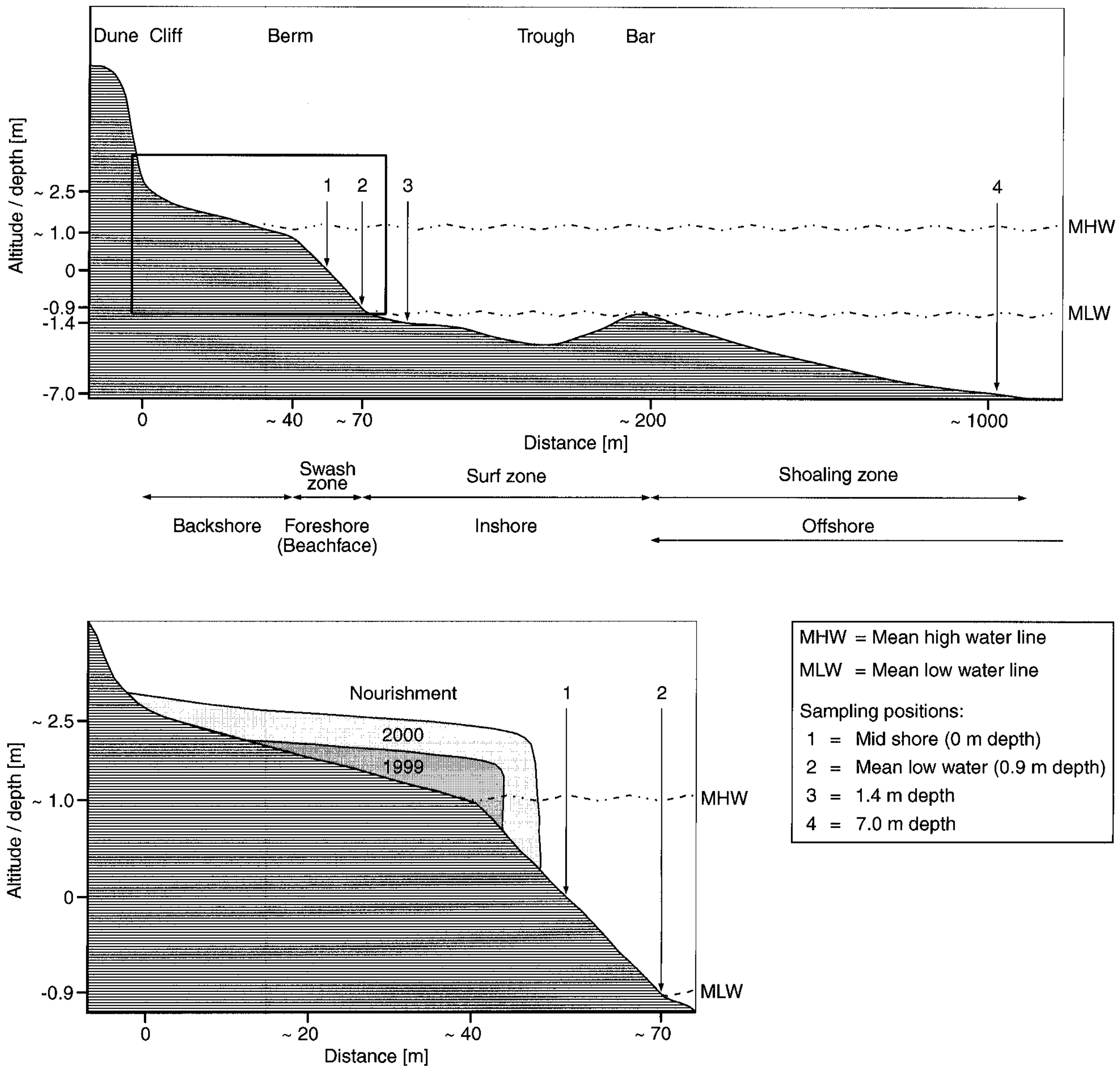


Fig. 2: Schematic profile across the Sylt shore with sampling sites. – Terminology for zones according to SHORT (1999). In the detail below, the amount of replenished sand and the resulting beach profiles in 1999 and 2000 are schematically indicated.

nourished region, which is 2 km long. Replenishments took place in the summers of 1999 and 2000. Earlier, this region had already been nourished in 1988 and 1993. The selected reference site begins 1.5 km south of the nourished region. This site had been nourished once before in 1992. Residual longshore currents are directed northward. Before sand replenishments started, the shoreline had retreated by 1-2 m per year over the last century (DETTE & GÄRTNER 1987). The studied areas are characterized by a steep beachface (slope of 2-4°; Fig. 2). An intermittent sand bar runs parallel to the beach at a horizontal distance of about 200 m from the mean low water line. Further offshore, the profile is rather steep, with the 6 m depth contour lying within 1 km from the shoreline. The morphodynamic states of the shore resemble intermediate types ("longshore bar-through" and "rhythmic bar and beach" during winter; "transverse bar and rip" and "low tide terrace" during summer), which are assumed to be the most dynamic ones (SHORT & WRIGHT 1983; SHORT 1999). Dynamics are intensified by the beach nourishment, which constitutes a morphodynamic state not in equilibrium. The sediment of the shore consists of medium to coarse sand (median diameter (Md) = 0.56 ± 0.33 mm; Wentworth grade

Fig. 1: Study sites at the northern part of the barrier island of Sylt in the eastern North Sea. – Nourished site and reference site are 1 km in shore length each. The nourished region is 2 km in shore length, with replenishments in the summers of 1999 and 2000. The reference site begins 1.5 km south of the nourished region.

classification) with a decrease in grain size towards the subtidal (MENN 2002). It is moderately well sorted in the intertidal and well sorted in the subtidal (sorting classes according to GRAY 1981). A blackish sulphide layer in the sediment is apparent in the deeper subtidal only (MENN 2002).

Beach Nourishment

The beach nourishment in 1999 was completed over a period of six weeks (May 18 to July 30). During this phase, 159,000 m^3 of dredged sand were hydraulically deposited directly onto the beach along 2 km of shoreline. The material was dredged 6 km offshore at the source area Westerland II (54°55'43"N 008°09'46"E, 54°55'32"N 008°11'33"E, 54°53'09"N 008°10'47"E, 54°53'21"N 008°08'56"E) by a hopper bagger, transported to the beach and pumped as a water slurry via a movable pipeline onto the beach. The sediment-water slurry was released from a diffuser head at the end of the pipeline into a basin at the beach, prepared by bulldozers. The water flew back into the sea while the sediment stayed, and a new beach profile was modelled by the bulldozers. In 2000 (May 22 to June 20) a nourishment adding 351,000 m^3 of sand was conducted in the same way. After the completion of the operations, a new cliff of approximately 1.5 m height in 1999 and of 2.5-3.0 m height in 2000 developed (Fig. 2). The beach immediately began to revert to its original morphology. The steeper profiles from the sediment filling cause beach morphometries to become more reflective, thereby potentially increasing wave disturbance and sediment transport dynamics (BROWN & MCLACHLAN 1990; RAKOCINSKI et al. 1996). The nourished material consisted of moderately well sorted sand with a medium grain size of 0.45 ± 0.16 mm and 0.36 ± 0.18 mm in 1999 and 2000, respectively. In both years these grain sizes were close to the mean of the resident sediment of the entire shore (1999: 0.51 ± 0.29 mm; 2000: 0.54 ± 0.27 mm). The nourished material was grey and black, indicating that it came from a reduced sediment layer. It contained no living meio- or macrofauna.

Sampling

To assess the impact of beach nourishment on the infauna, an "area by time" design (see NELSON 1993) was used. A nourished site and a reference site were studied simultaneously. Since the selected reference site lies about 1.5 km south of the nourished region (Fig. 1) and residual currents would transport sediment northward, the nourishment is extremely unlikely to influence the reference site. Interspersing reference sites between nourished areas was impossible with only a single impacted site available.

A pre-nourishment survey of meio- and macrofauna was conducted in April 1999, one month prior to the start of the operation (Fig. 3). In October 1999, three months after completion of the operation, the first post-nourishment sampling for meio- and macrofauna was done. Macrofauna was sampled again nine months after the impact, in April 2000. When the financial support for this study was unexpectedly extended just before the second nourishment started, another meiofauna pre-nourishment sampling could be carried out in May 2000. Accordingly, the previous post-nourishment sampling for macrofauna, which had followed the first replenishment in April 2000, was now redefined as being at the same time the pre-nourishment sampling for the second replenishment. Post-nourishment sampling for both meio- and macrofauna was done four months after the second nourishment (October 2000), and macrofauna was sampled again nine months after the operation (March 2001).

To assess the effect of the operations on the infauna from mid shore to 7 m depth, four positions were sampled: (1) mid shore (0 m), (2) mean low water (0.9 m depth), (3) 1.4 m depth and (4) 7 m depth (Fig. 2). During all sampling occasions these positions were located seaward of the new cliff, which developed immediately after the nourishments. Each position was replicated randomly six times within 1 km of shoreline length. For meiofauna sampling, replicates were taken using a core of 10 cm^2 cross area to a sediment depth of 30 cm. Macrofauna was sampled at 1.4 m and 7 m depths in 1999 and in 2000/2001 also at mean low water (0.9 m depth) (Fig. 3), because macrofauna at this beach is of very low abundance above the mean low water line (MENN 2002). Each replicate consisted of four cores of 50 cm^2, pooled to 200 cm^2 cross area, down to a depth of 20 cm.

In the laboratory, meiofauna was extracted from the sediment using the SMB-method (NOLDT & WEHRENBERG 1984), which is specifically adapted to include soft-bodied meiofauna. A mesh size of 63 µm was used. Major taxa were sorted and plathelminths and polychaetes were identified to species level. "Meiofauna" here includes permanent and temporary meiofauna (juvenile polychaetes). Due to low abundances, acarids, oligochaetes, nemerteans, bivalves and gastrotrichs are summarized under the category "others" in 1999. In 2000, the abundance category "others" comprises oligochaetes and nemerteans only. This was due to the absence of acarids, bivalves and gastrotrichs during this sampling period.

Macrofauna samples were sieved trough a 1 mm mesh. The animals were sorted alive, counted and identified to species level whenever possible. *Crangon crangon* and *Carcinus maenas* (both Decapoda), which belong to the mobile surface fauna but also burrow in the sediment, were included in the analysis. In 1999/2000, macrofaunal nemerteans, decapods and bivalves are summarized under the category "others", while in 2000/2001 this category comprises decapods and bivalves.

In both years, replenished material was directly collected from the diffuser head of the pipeline and searched for living meio- and macrofauna (800 cm^3 for meiofauna, 8000 cm^3 for macrofauna).

Simultaneously to all meio- and macrofauna sampling occasions, sediment samples (one core of 10 cm^2 cross area to 10 cm sediment depth) were taken for grain size analysis at the same sampling positions as for the infauna (Fig. 3). Additionally, 14 replicates of the replenished material were sampled for grain size analysis. Granulometric analyses were carried out by dry sieving. Mean grain sizes and sorting coefficients were calculated according to BUCHANAN (1984).

Statistical Analysis

Average numbers of individuals (= abundance) and species (= species density) per 10 cm^2 and 200 cm^2 for meio- and macrofauna, respectively, were calculated for each sampling occasion at the nourished and reference site. Each transect position was considered separately. For meiofauna, species

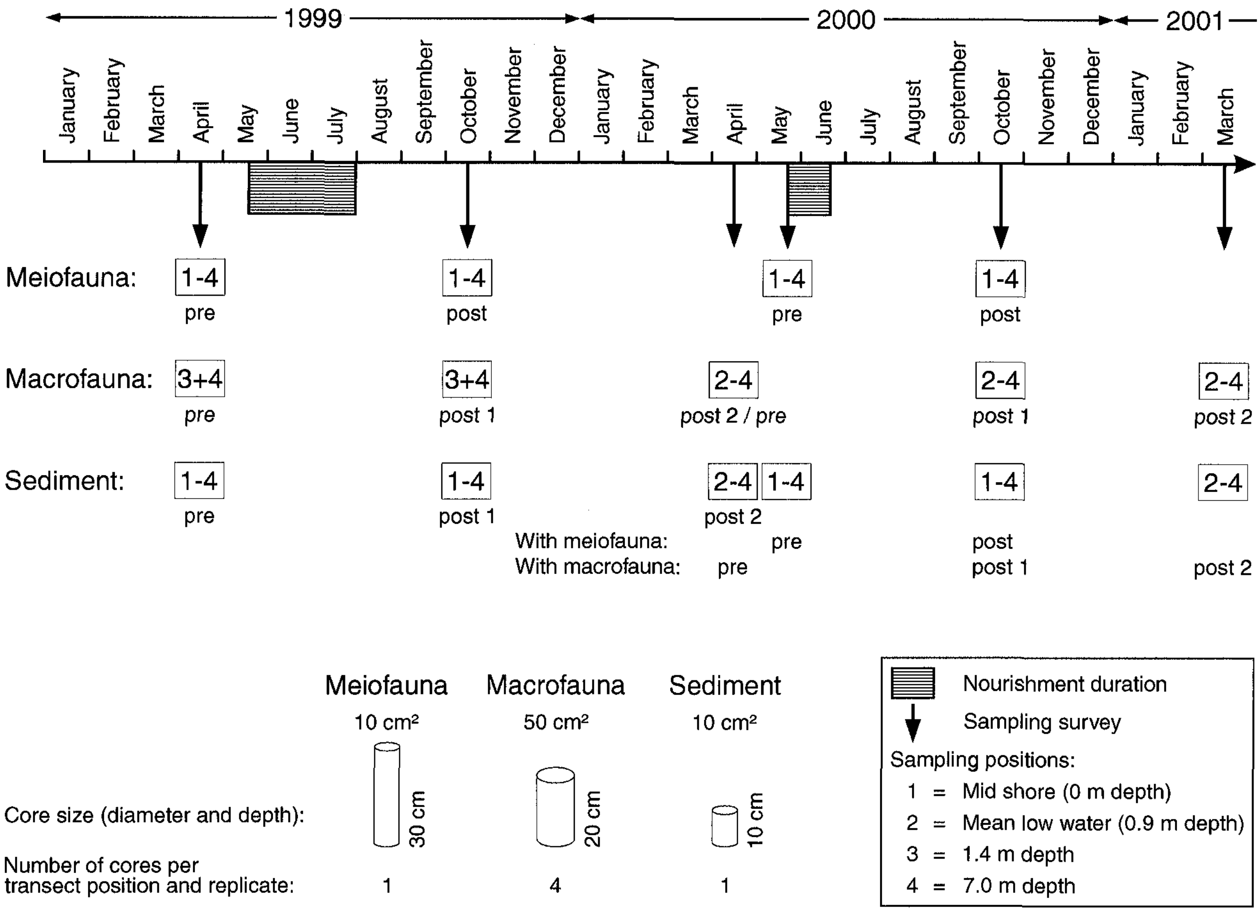


Fig. 3: Time schedule of the sampling surveys and details of cores taken for samples. – pre = pre-nourishment surveys, usually one month before (in one case directly before) the operation; post and post 1 = post-nourishment surveys, three months after the first and four months after the second operation; post 2 = final post-nourishment surveys nine months after the operation.

density was based on plathelminths and polychaetes, while for macrofauna all specimens were determined to species level. Analysis of variance (ANOVA) was used to test for differences in abundances, species density and grain size between the nourished and the reference site within each survey and between sampling occasions within each site. Different levels within a significant parameter were analysed using Tukey's Honest-Significant-Difference (HSD) multiple comparison test. To test for homoscedasticity of variances, Cochran's test was used, and data of the dependent variables were transformed (Tabs. 3, 4, 6 and 7). When variances remained heterogeneous despite of the transformation, the H-Test (Kruskal and Wallis) was used, followed by pair-wise Wilcoxon's non-parametric U-Tests (Sachs 1984). Statistical significance was assumed at $p < 0.025$ for ANOVA (Bonferroni-procedure for multiple comparisons; Sokal & Rohlf 1995), at $p < 0.05$ for H-Test, and at $p < 0.025/0.017$ (meio-/macrofauna) for the following pairwise U-Tests.

Results

Grain Size Comparison for the First Nourishment

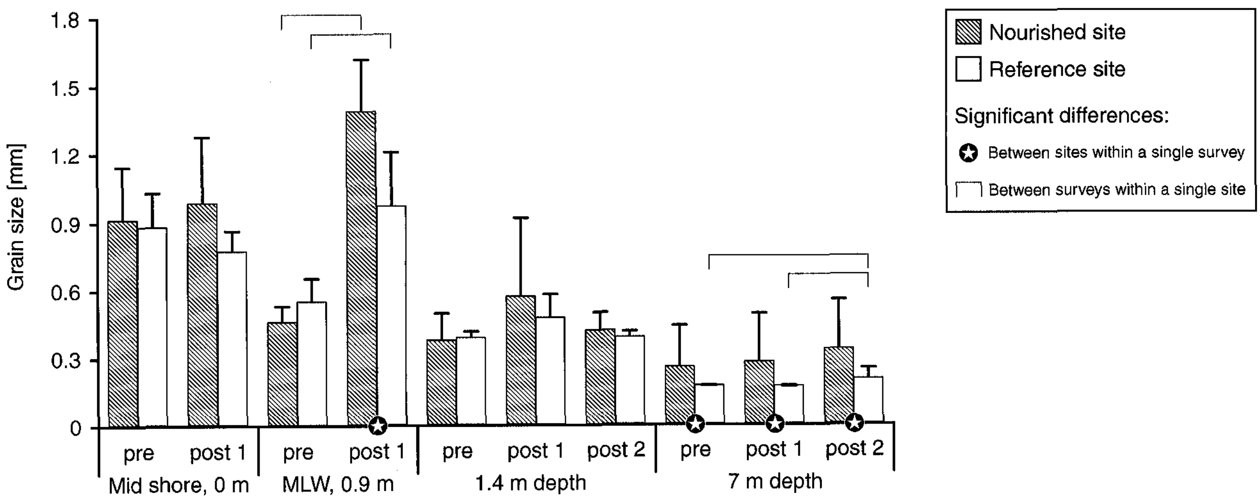
After the nourishment in 1999, the sediment at mean low water (MLW) was coarser at the nourished than at the reference site (Fig. 4, Tab. 1). No differences in grain size between sites had been detected before the operation. However, grain size had increased at both sites. Also at 7 m depth, the sediment was coarser at the nourished than at the reference site. This had already been the case before replenishment. No differences in grain size between sites and surveys were noticed at mid shore and 1.4 m depth.

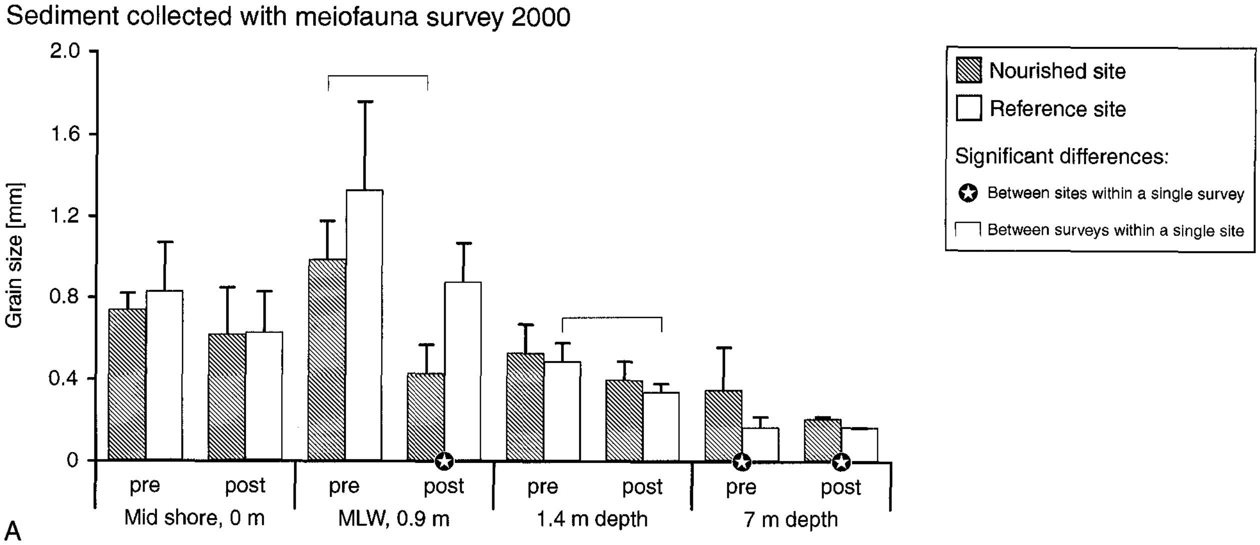
Grain Size Comparison for the Second Nourishment

The fact that there were two separate pre-nourishment sediment samplings at different times before the second replenishment, one carried out with the macrofauna survey (April 2000) and the other with the meiofauna survey (May 2000), required performing the grain size analysis for the second nourishment in two parts, as is shown in Fig. 5 A and B. Note that the data of "post" in the meiofauna survey are the same as "post 1" in the macrofauna survey, i.e. the ones gathered four months after nourishment in October 2000 (cf. Fig. 3).

Table 1: Statistics of median grain size comparisons at the nourished site and the reference site for both nourishments. – H-Test: df = 3, U-Test: df = 1. For occasions of pre- and post-nourishment samplings see Fig. 3.

	One-way ANOVA [p <]	One-way ANOVA df	One-way ANOVA F	HSD-Test [p <]	H-Test [p <]	U-Test [p <]
First nourishment (1999/2000)						
Mean low water						
post 1: nourished site / reference site	0.01	1	9.53			
Nourished site: pre / post	0.00001	1	112.83			
Reference site: pre / post	0.01	1	16.49			
7 m depth						
pre: nourished site / reference site						0.017
post 1: nourished site / reference site						0.017
post 2: nourished site / reference site						0.017
Reference site: pre / post 1					0.001	0.01
Reference site: post 1 / post 2					0.001	0.01
Second nourishment (2000/2001)						
A: Sediment collected with meiofauna						
Mean low water						
post: nourished site / reference site	0.001	1	21.41			
Nourished site: pre / post	0.001	1	32.50			
1.4 m depth						
Reference site: pre / post	0.01	1	14.34			
7 m depth						
pre: nourished site / reference site						0.01
post: nourished site / reference site						0.01
B: Sediment collected with macrofauna						
Mean low water						
post 1: nourished site / reference site	0.001	1	21.41			
Reference site: pre / post 1	0.001	3	12.00	0.01		
Reference site: post 1 / post 2	0.001	3	12.00	0.01		
1.4 m depth						
Reference site: pre / post 1	0.01	3	6.58	0.01		
7 m depth						
pre: nourished site / reference site						0.01
post 1: nourished site / reference site						0.01
post 2: nourished site / reference site						0.01
Reference site: pre / post 1					0.001	0.01
Reference site: pre / post 2					0.001	0.01





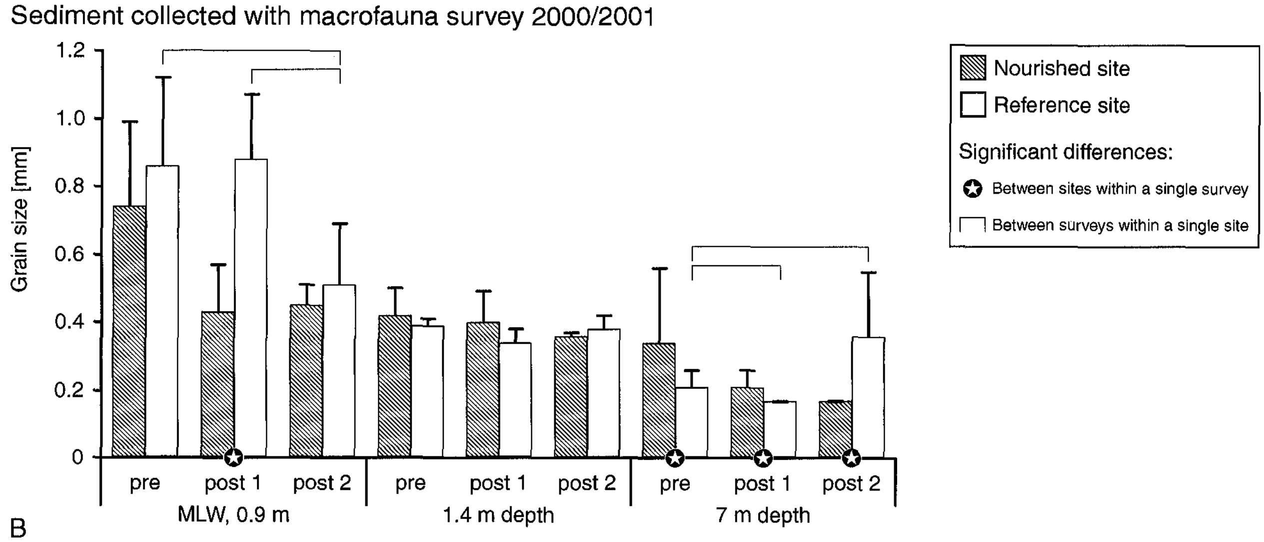


Fig. 5: Second nourishment: Comparison of sediment grain size at nourished and reference site across the shore. – Data given as arithmetic means with standard deviations of 6 replicates per survey. – A: Sediment collected with meiofauna survey. Samples taken directly before (= pre, May 2000) and four months after (= post, October 2000) the operation. – B: Sediment collected with macrofauna survey. Samples taken one month before (= pre, April 2000), four months after (= post 1, October 2000) and nine months after (= post 2, March 2001) the operation.

Grain size data collected with the meiofauna sampling show that the mean grain size at MLW was smaller at the nourished than at the reference site after replenishment (Fig. 5 A, Tab. 1). No difference in grain size between the sites had been noticed in the pre-nourishment survey. Grain size decreased significantly at the nourished site while no significant difference was found at the reference site. At 7 m depth, the sediment was coarser at the nourished site in all surveys. No differences in grain size between the sites were detected at mid shore and at 1.4 m depth.

Similarly, the sediment sampled together with macrofauna at MLW was finer at the nourished than at the reference site in the first post-nourishment sampling (Fig. 5 B, Tab. 1). No difference in grain size between the sites was noticed in the pre- and the second post-nourishment survey. Also, grain sizes showed no significant difference between the sampling occasions at the nourished site. At the reference site, however, grain size was finer in the second post-nourishment survey compared to both previous surveys. At 7 m depth, grain size was different between the sites, but not consistently between the surveys. At 1.4 m depth, no difference of grain size between sites and surveys was noticed.

In summary, at MLW both nourishments affected mean grain size.

Fig. 4: First nourishment: Comparison of sediment grain size at nourished and reference site across the shore. – Samples taken one month before (= pre, April 1999), three months after (= post 1, October 1999) and nine months after (= post 2, April 2000) the operation. Data given as arithmetic means with standard deviations of 6 replicates per survey.

Table 2: Summary for meiofauna: Significant differences in abundance and species density of plathelminths and polychaetes between nourished and reference site per survey. – R = the reference site has the higher values of total meiofaunal abundance or species density (plathelminths and polychaetes); N = the nourished site has the higher values of these parameters; – = no difference between the sites. Letters following the colon indicate differences of single taxa between sites: Os = Ostracoda, Co = Copepoda, Po = Polychaeta, Ne = Nematoda, Pl = Plathelminthes.

	First nourishment (1999)		Second nourishment (2000)	
	pre April 1999	post October 1999	pre May 2000	post October 2000
Abundance				
Mid shore	R: Os	–	–	–
Mean low water	R: Co, Po, Os	–	–	–
1.4 m depth	–	–	–	R: Co
7 m depth	R: Ne	–	–	–
Species density				
Mid shore	–	N	–	R: Po
Mean low water	–	–	–	–
1.4 m depth	–	–	N: Po	–
7 m depth	–	N: Pl	–	–

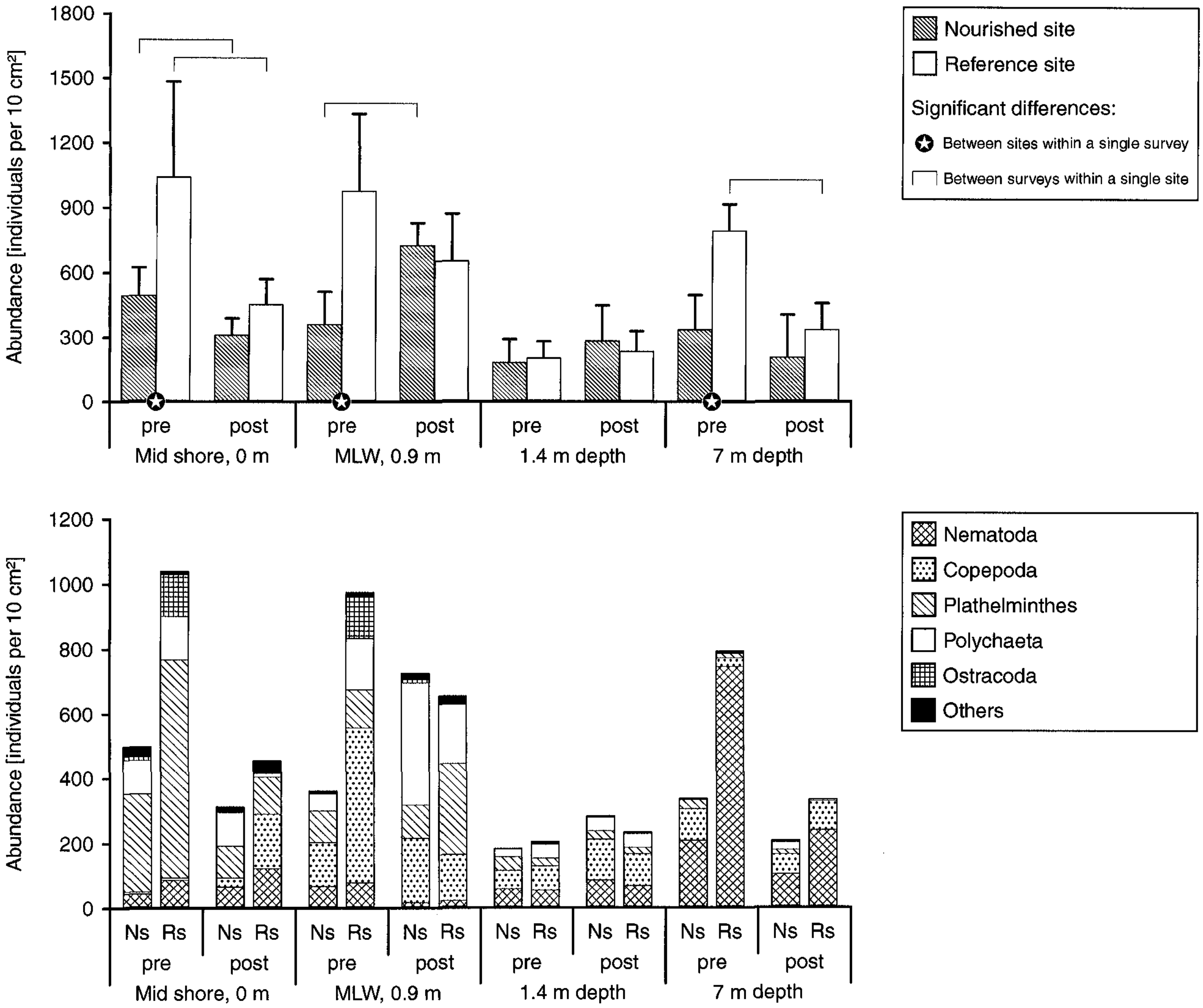


Fig. 6: First nourishment: Comparison of total meiofaunal abundance and abundance of major taxa per 10 cm^2 at nourished and reference site across the shore. – Samples taken one month before (= pre, April 1999) and three months after (= post, October 1999) the operation. Data given as arithmetic means with standard deviations of 6 replicates per survey. Others = acarids, oligochaetes, nemerteans, bivalves and gastrotrichs.

Table 3: Statistics of total meiofaunal abundance and abundance of major taxa per 10 cm^2 at the nourished site and the reference site for both nourishments. – Trans = data transformation; sq.r. = square root; LN = natural logarithm; One-way ANOVA and U-Test: df = 1; * = assumed to indicate a tendency. No significant differences between sites and surveys were noticed at 1.4 m depth for the first and at 7 m depth for the second nourishment. For occasions of pre- and post-nourishment samplings see Fig. 3.

First nourishment (1999)

	One-way ANOVA			U-Test
	[p <]	F	Trans	[p <]
Mid shore				
pre				
Total	0.01	9.89	sq.r.	
Ostracoda	0.025	7.82	sq.r.	
Nourished site				
Total	0.025	9.41		
Copepoda	0.025	8.12		
Plathelminthes	0.01	15.07	LN	
Reference site				
Total	0.01	12.89	LN	
Copepoda				0.01
Plathelminthes	0.001	28.85	LN	
Polychaeta	0.01	9.97	sq.r.	
Ostracoda				0.01
Others	0.01	19.22		
Mean low water				
pre				
Total	0.01	14.94		
Copepoda	0.01	11.75		
Polychaeta	0.01	10.80		
Ostracoda				0.01
post				
Polychaeta	0.03*	5.15		
Nourished site				
Total	0.001	23.70		
Nematoda	0.01	20.49		
Polychaeta	0.001	27.15	sq.r.	
7 m depth				
pre				
Total	0.001	30.92		
Nematoda	0.0001	77.77		
Plathelminthes	0.01	16.11	sq.r.	
Reference site				
Total	0.0001	42.33		
Nematoda	0.00001	63.49		
Copepoda	0.01	11.96		
Plathelminthes				0.01

Second nourishment (2000)

	One-way ANOVA			U-Test
	[p <]	F	Trans	[p <]
Mid shore				
Nourished site				
Total	0.001	30.82		
Plathelminthes	0.01	13.14		
Nematoda	0.01	9.76		
Polychaeta				0.025
Reference site				
Total	0.03*	6.21		
Plathelminthes	0.01	10.11		
Mean low water				
Nourished site				
Total	0.001	48.97		
Polychaeta	0.0001	52.70	sq.r.	
Copepoda	0.01	12.89	sq.r.	
Plathelminthes	0.0001	73.48	sq.r.	
Ostracoda				0.025
Others				0.025
Reference site				
Total	0.025	6.72		
Polychaeta	0.03*	5.79	sq.r.	
1.4 m depth				
pre				
Nematoda				0.01
Plathelminthes				0.01
Polychaeta	0.001	19.20	sq.r.	
Ostracoda				0.01
post				
Total	0.025	8.84		
Copepoda				0.03*
Nourished site				
Total				0.01
Nematoda	0.01			
Copepoda	0.0001	41.28	sq.r.	
Polychaeta	0.01			
Ostracoda	0.01			

Meiofauna

A summary of the meiofauna results revealed no consistent trend in meiofaunal abundance and species density of plathelminths and polychaetes between the nourished and the reference site (Tab. 2). Some major taxa had higher abundances at the reference site before the nourishment took place, and in one case copepods were more abundant thereafter. Species density of plathelminths and polychaetes was higher at the nourished site at two positions after the first nourishment in 1999, while no differences between sites had been evident before the operation. In the surveys before and after the second nourishment, species density of polychaetes was higher at the nourished site at 1.4 m depth before the operation, while it was higher at the reference site at mid shore after the nourishment.

Abundance Comparison for the First Nourishment

No difference in total meiofaunal abundance at mid shore, MLW and 7 m depth was detected between the nourished and the reference site after the operation in 1999 (Fig. 6, Tab. 3). However, abundance had already been lower at the nourished than at the reference site before the nourishment. At mid shore, ostracods had shown a significant difference between the sites before the nourishment. At both sites a decrease of abundances from pre- to post-nourishment sampling was

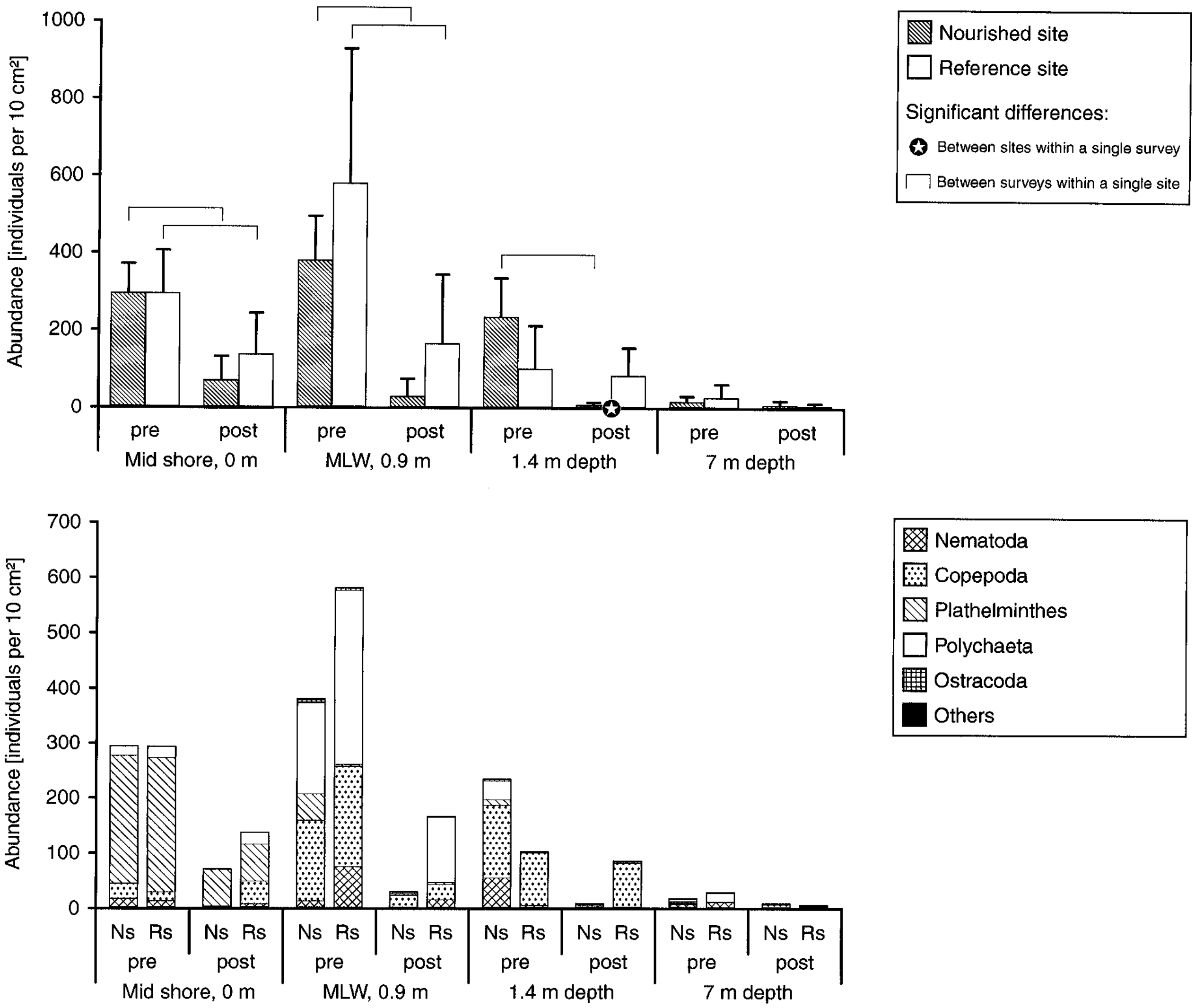


Fig. 7: Second nourishment: Comparison of total meiofaunal abundance and abundance of major taxa per 10 cm^2 at nourished and reference site across the shore. – Samples taken directly before (= pre, May 2000) and four months after (= post, October 2000) the operation. Data given as arithmetic means with standard deviations of 6 replicates per survey. Others = oligochaetes and nemerteans.

noticed, namely in copepods and plathelminths at the nourished site and also in polychaetes, ostracods and "others" at the reference site. At MLW, copepod, polychaete and ostracod abundances had already been lower at the nourished than at the reference site before the operation. At this position, abundances increased significantly at the nourished site after replenishment, especially those of interstitial polychaetes (*Hesionides arenarea* and *Trilobodrilus axi*). At the reference site no differences were noticed. At 7 m depth, nematodes had different abundances between the sites in the pre-nourishment survey, and abundances decreased after the nourishment at the reference site. Meiofaunal abundance at 1.4 m depth showed no differences between sites and surveys.

Abundance Comparison for the Second Nourishment

After the nourishment in 2000, total meiofaunal abundance at 1.4 m depth had decreased at the nourished compared to the reference site, which is due to reduced abundance of copepods (Fig. 7, Tab. 3). No difference of total abundances between the sites had been noticed in the pre-nourishment survey, although abundances of nematodes, plathelminths, polychaetes and ostracods had differed between nourished and reference site. At the nourished site, abundance decreased after the impact, while it remained constant at the reference site. At the former, abundances of nematodes, copepods, polychaetes and ostracods differed between sampling occasions. At mid shore, MLW and 7 m depth, total abundance showed no difference between nourished and reference site in both surveys. A decrease of abundances from pre- to post-nourishment surveys was noticed at both sites at mid shore and MLW.

Species Density Comparison for the First Nourishment

Meiofaunal species density of plathelminths and polychaetes at mid shore and at 7 m depth was higher at the nourished than at the reference site after replenishment in 1999 (Fig. 8, Tab. 4). No significant difference in species

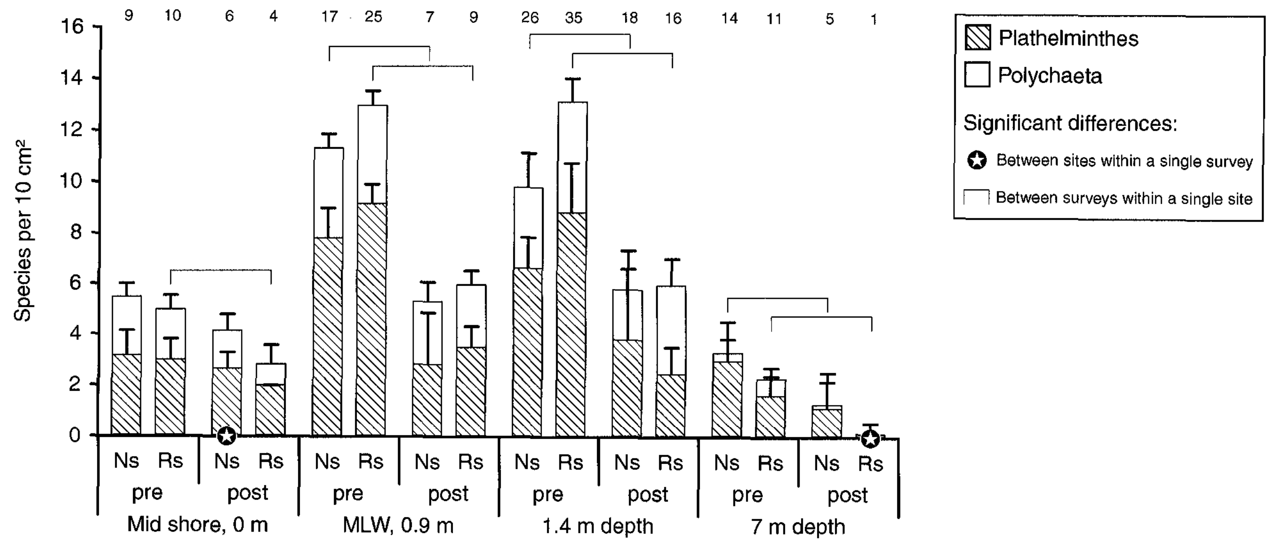


Fig. 8: First nourishment: Comparison of meiofaunal species density of plathelminths and polychaetes per 10 cm² at nourished and reference site across the shore. – Samples taken one month before (= pre, April 1999) and three months after (= post, October 1999) the operation. Data given as arithmetic means with standard deviations of 6 replicates per survey. Total numbers of species are shown above each column.

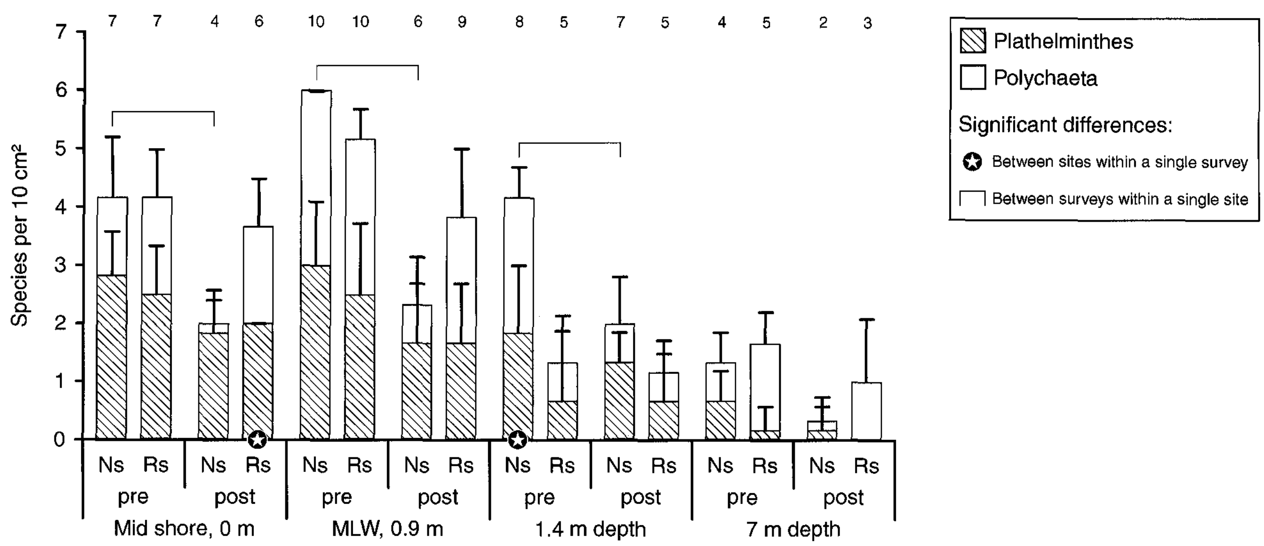


Fig. 9: Second nourishment: Comparison of meiofaunal species density of plathelminths and polychaetes per 10 cm² at nourished and reference site across the shore. – Samples taken directly before (= pre, May 2000) and four months after (= post, October 2000) the operation. Data given as arithmetic means with standard deviations of 6 replicates per survey. Total numbers of species are shown above each column.

density between the sites had been noticed before the impact. At 7 m depth, the difference in the post-nourishment survey was caused by plathelminths. A decrease in species density was noticed after the nourishment at mid shore at the reference site and at MLW, 1.4 m and 7 m depth at both sites.

Species Density Comparison for the Second Nourishment

In 2000, meiofaunal species density at mid shore was lower at the nourished than at the reference site after replenishment (Fig. 9, Tab. 4). No difference in species density between the sites had been noticed in the pre-nourishment survey. At 1.4 m depth, species density had been higher at the nourished than at the reference site before the operation, while no difference between sites was detected afterwards. A significant decrease in species density from the pre- to the post-nourishment survey was noticed at the nourished site at mid shore, MLW and 1.4 m depth, while it remained constant at the reference site. All these differences in species density were caused by polychaetes. At the nourished mid shore, it was particularly the absence of archiannelids (*Trilobodrilus axi*, *Protodrilus* sp.) after the nourishment that caused the difference between the sites. At MLW and 7 m depth, no differences in species density between sites within surveys were noticed.

Table 4: Statistics of meiofaunal species density (plathelminths and polychaetes) per 10 cm^2 at the nourished site and the reference site for both nourishments. – Total = total of plathelminths and polychaetes. Square root transformation: 1.4 m depth reference site plathelminths, 7 m depth nourished site total and reference site total. One-way ANOVA and U-Test: df = 1. No significant differences between sites and surveys were detected at 7 m depth in 2000. For occasions of pre- and post-nourishment samplings see Fig. 3.

First nourishment (1999)

	One-way ANOVA [p <]	F	U-Test [p <]
Mid shore			
post			
Total	0.025	6.96	
Nourished site			
Polychaeta	0.025	7.35	
Reference site			
Total	0.01	15.94	
Polychaeta	0.025	8.45	
Mean low water			
Nourished site			
Total	0.0001	45.17	
Polychaeta	0.01	10.00	
Plathelminthes	0.00001	77.59	
Reference site			
Total	0.001	43.24	
Polychaeta	0.01	12.31	
Plathelminthes	0.0001	39.59	
1.4 m depth			
Nourished site			
Total	0.025	8.24	
Plathelminthes	0.025	9.20	
Reference site			
Total	0.01	17.74	
Plathelminthes	0.001	22.65	
7 m depth			
post			
Total	0.001	26.65	
Plathelminthes			0.01
Nourished site			
Total	0.01	11.50	
Plathelminthes	0.025	6.80	
Reference site			
Total	0.01	12.05	
Plathelminthes			0.01

Second nourishment (2000)

	One-way ANOVA [p <]	F	U-Test [p <]
Mid shore			
post			
Total	0.01	12.37	
Polychaeta	0.01	16.20	
Nourished site			
Total	0.01	11.95	
Polychaeta	0.025	6.62	
Mean low water			
Nourished site			
Total	0.001	26.30	
Polychaeta			0.01
1.4 m depth			
pre			
Total	0.01	9.97	
Polychaeta	0.01	17.86	
Nourished site			
Total	0.01	13.00	
Polychaeta	0.01	17.86	

Macrofauna

Significant differences in macrofaunal abundances and species densities primarily revealed a decline of polychaetes at the offshore position of the nourished site after the second replenishment in 2000 (Tab. 5).

Abundance Comparison for the First Nourishment

Macrofaunal abundance at 1.4 m depth was lower at the nourished than at the reference site three months after the first nourishment (Fig. 10, Tab. 6), which is mainly attributable to a decrease in abundances of the isopod *Eurydice pulchra* and the polychaete *Scolelepis squamata*. No difference in abundance between the sites had been detected before the operation. In the second post-nourishment sampling, total abundance was higher at the nourished than at the reference site. However, at both sites abundances were lower in the second post-nourishment survey than on previous sampling occasions. At 7 m depth, no differences in abundance between sites and surveys were noticed.

Abundance Comparison for the Second Nourishment

Total macrofaunal abundance at MLW was higher at the nourished than at the reference site in the second post-

Table 5: Summary for macrofauna: Significant differences in abundance and species density between nourished and reference site per survey. – R = the reference site has the higher values of total abundance or total species density; N = the nourished site has the higher values of these parameters; – = no difference between the sites. Letters following the colon indicate differences of single taxa between the sites: Is = Isopoda, Po = Polychaeta, Am = Amphipoda. n.s. = this positions was not sampled in 1999.

	First nourishment (1999/2000)			Second nourishment (2000/2001)		
	pre April 1999	post 1 October 1999	post 2 April 2000	pre April 2000	post 1 October 2000	post 2 March 2001
Abundance						
Mean low water	n.s.	n.s.	n.s.	–	–	N: Po
1.4 m depth	–	R: Is, Po	N	N	–	–
7 m depth	–	–	–	–	R: Po	R: Po
Species density						
Mean low water	n.s.	n.s.	n.s.	–	–	N
1.4 m depth	–	–	–	–	R: Am	–
7 m depth	–	–	–	–	R: Po	R: Po

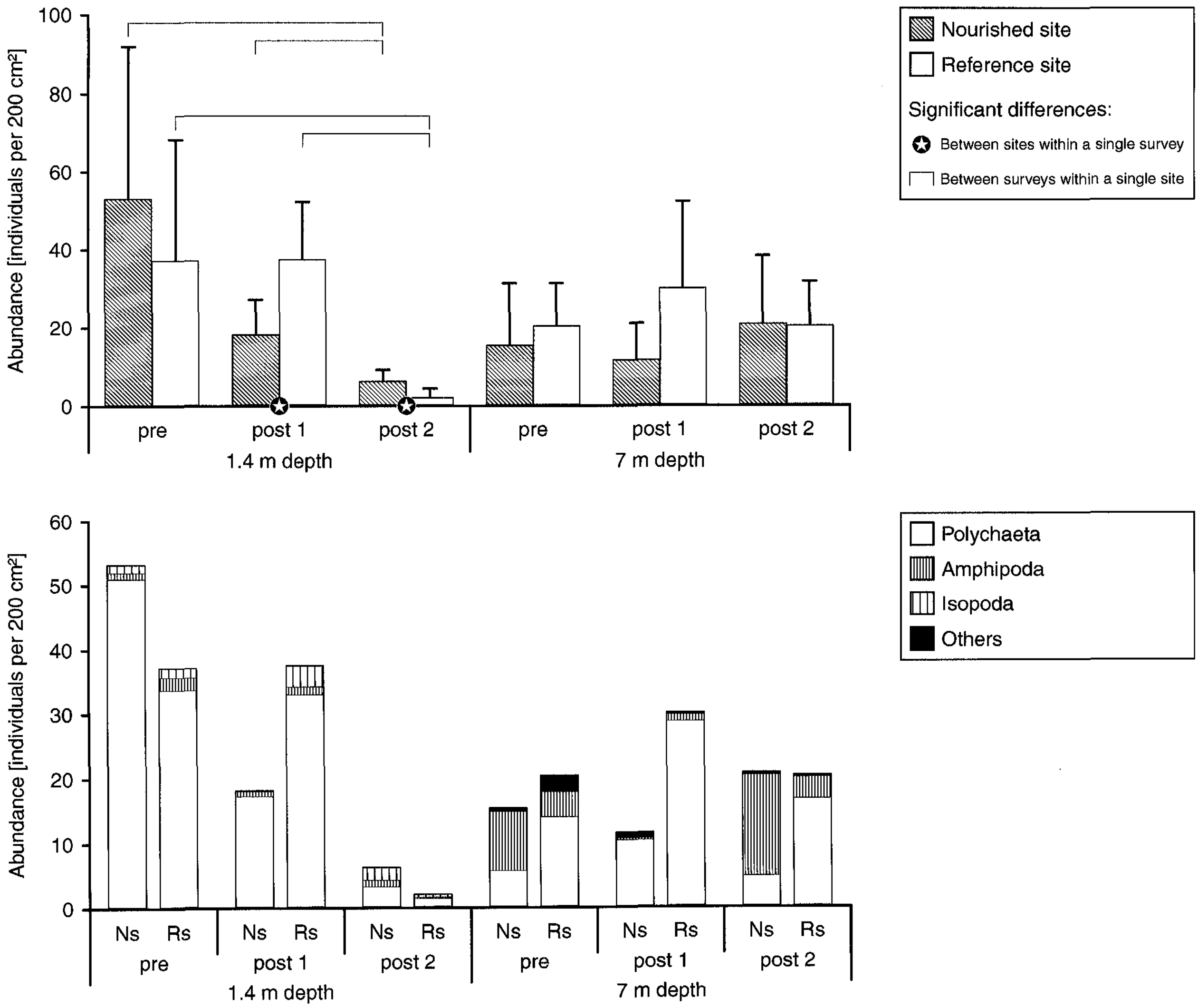


Fig. 10: First nourishment: Comparison of total macrofaunal abundance and abundance of major taxa per 200 cm^2 at nourished and reference site at two sampling positions. – Samples taken one month before (= pre, April 1999), three months after (= post 1, October 1999) and nine months after (= post 2, April 2000) the operation. Data given as arithmetic means with standard deviations of 6 replicates per survey. Others = nemerteans, decapods and bivalves.

Table 6: Statistics of total macrofaunal abundance and abundance of major taxa per 200 cm² at the nourished site and the reference site in the studies for both nourishments. – Trans = data transformation; sq.r. = square root; H-Test: df = 3, U-Test: df = 1; * = assumed to indicate a tendency. No significant differences between sites and surveys were noticed at 7 m depth for the first nourishment. For occasions of pre- and post-nourishment samplings see Fig. 3.

	One-way ANOVA						
	[*p* <]	df	F	HSD-Test [*p* <]	Trans	H-Test [*p* <]	U-Test [*p* <]
First nourishment (1999/2000)							
1.4 m depth							
post 1: Total	0.02	1	7.55				
post 1: Isopoda	0.01	1	11.01		sq.r.		
post 1: Polychaeta	0.03*	1	4.61				
post 2: Total	0.02	1	7.64				
Nourished site total: pre / post 2						0.01	0.01
Nourished site total: post 1 / post 2						0.01	0.01
Nourished site pre / post 2: Polychaeta						0.01	0.01
Nourished site post 1 / post 2: Polychaeta						0.01	0.01
Reference site total: pre / post 2						0.01	0.001
Reference site total: post 1 / post 2						0.01	0.001
Reference site pre / post 2: Polychaeta						0.01	0.01
Reference site pre / post 2: Amphipoda	0.025	3	4.85	0.017			
Reference site post 1 / post 2: Polychaeta						0.01	0.01
Second nourishment (2000/2001)							
Mean low water							
post 2	0.01	1	9.31				
post 2: Polychaeta	0.025	1	6.74				
1.4 m depth							
pre	0.025	1	8.89				
Reference site: pre / post 1	0.01	3	7.14	0.01	sq.r.		
Reference site pre / post 1: Polychaeta	0.01	3	7.03	0.01	sq.r.		
Reference site pre / post 1: Amphipoda							0.017
7 m depth							
post 1: Total	0.01	1	14.70		sq.r.		
post 1: Polychaeta							0.01
post 2: Total	0.0001	1	51.26		sq.r.		
post 2: Polychaeta	0.001	1	29.60				
Nourished site total: pre / post 1	0.01	3	9.31	0.01	sq.r.		
Nourished site total: pre / post 2	0.01	3	9.31	0.01	sq.r.		
Nourished site pre / post 1: Polychaeta	0.01	3	9.54	0.01			
Nourished site pre / post 2: Polychaeta	0.01	3	9.54	0.01			
Nourished site pre / post 2: Amphipoda	0.01	3	5.74	0.025	sq.r.		

nourishment survey, mainly due to a decline of the polychaete *Scolelepis squamata*. No difference between the sites had been noticed before (Fig. 11, Tab. 6). At 1.4 m depth, no differences in abundance between the sites were detected in both post-nourishment surveys, while macrofaunal abundance had already been higher at the nourished than at the reference site before the nourishment. However, abundance had increased at the reference site until the first post-nourishment survey. No such increase occurred at the nourished site. At 7 m depth, total abundance was lower at the nourished than at the reference site in both post-nourishment surveys, while it had been similar before the operation. This was caused by varying polychaete abundances. At the nourished site, abundances decreased from the pre- to both post-nourishment samplings because of an almost total collapse of amphipods as well as by reduced polychaete abundances. No difference in abundances between surveys was detected at the reference site.

Species Density Comparison for the First and Second Nourishment

Total macrofaunal species density and that of major taxa showed no significant differences between sites and surveys in 1999 (Fig. 12).

With regard to the operation in 2000, macrofaunal species density at MLW was higher at the nourished than at the reference site in the second post-nourishment survey (Fig. 13, Tab. 7). No other differences were noticed at this position. At 1.4 m depth, species density was lower at the nourished than at the reference site three months after the operation, mainly attributable to reduced amphipod species density. No difference of species density between the sites was detected before and nine months after nourishment. Species density was similar at the nourished site in all surveys, while it increased

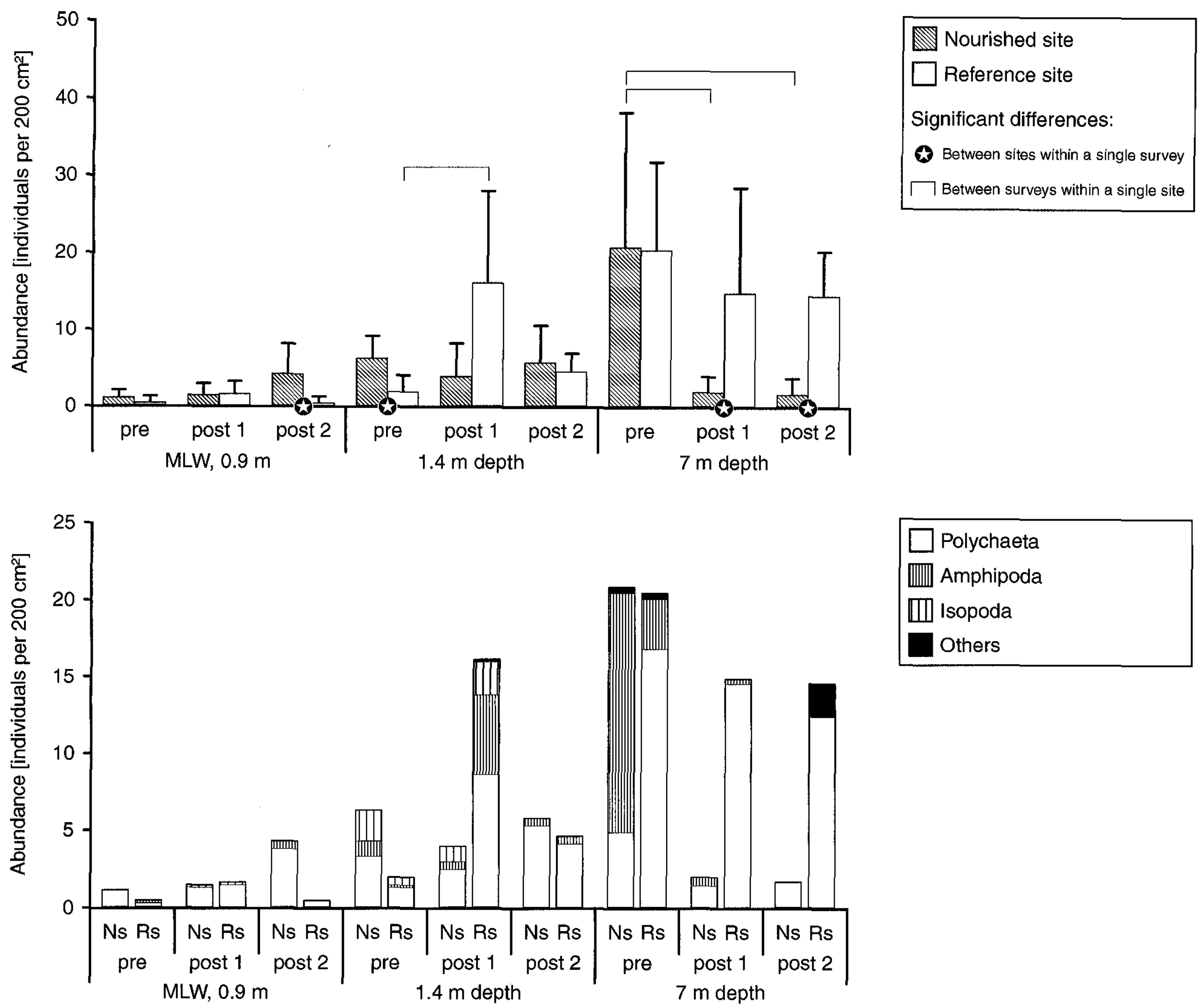


Fig. 11: Second nourishment: Comparison of total macrofaunal abundance and abundance of major taxa per 200 cm^2 at nourished and reference site at three sampling positions. – Samples taken one month before (= pre, April 2000), four months after (= post 1, October 2000) and nine months after (= post 2, March 2001) the operation. Data given as arithmetic means with standard deviations of 6 replicates per survey. Others = decapods and bivalves.

from the pre- to the first post-nourishment survey at the reference site. At 7 m depth, species density was lower at the nourished than at the reference site in both post-nourishment surveys, while no difference had been noticed before the replenishment. This was caused by changes in polychaete species density. No difference of species density between surveys was detected at the reference site, while at the nourished site species density declined.

Discussion

Effects on the Meiofauna Community

The meiofauna living high on the beach is buried beneath a sand deposit of 1-3 m height in the course of the nourishment operation. Due to meiofauna populations being sparse in the backshore region (SCHMIDT 1968; pers. obs.), this study focused on effects on the meiofauna occurring seaward of the area of sand refill. The organisms in the lower intertidal and subtidal may be affected by altered wave disturbance and sediment transport regimes as a result of the modified shape of the backshore (BROWN & MCLACHLAN 1990; RAKOCINSKI et al. 1996). However, the results from 1999 indicate no negative impact on the meiofauna (Tab. 2). In 2000, copepod abundance at 1.4 m depth and polychaete species density at mid shore were reduced four months after the operation. These effects could have been caused by the nourishment, but they

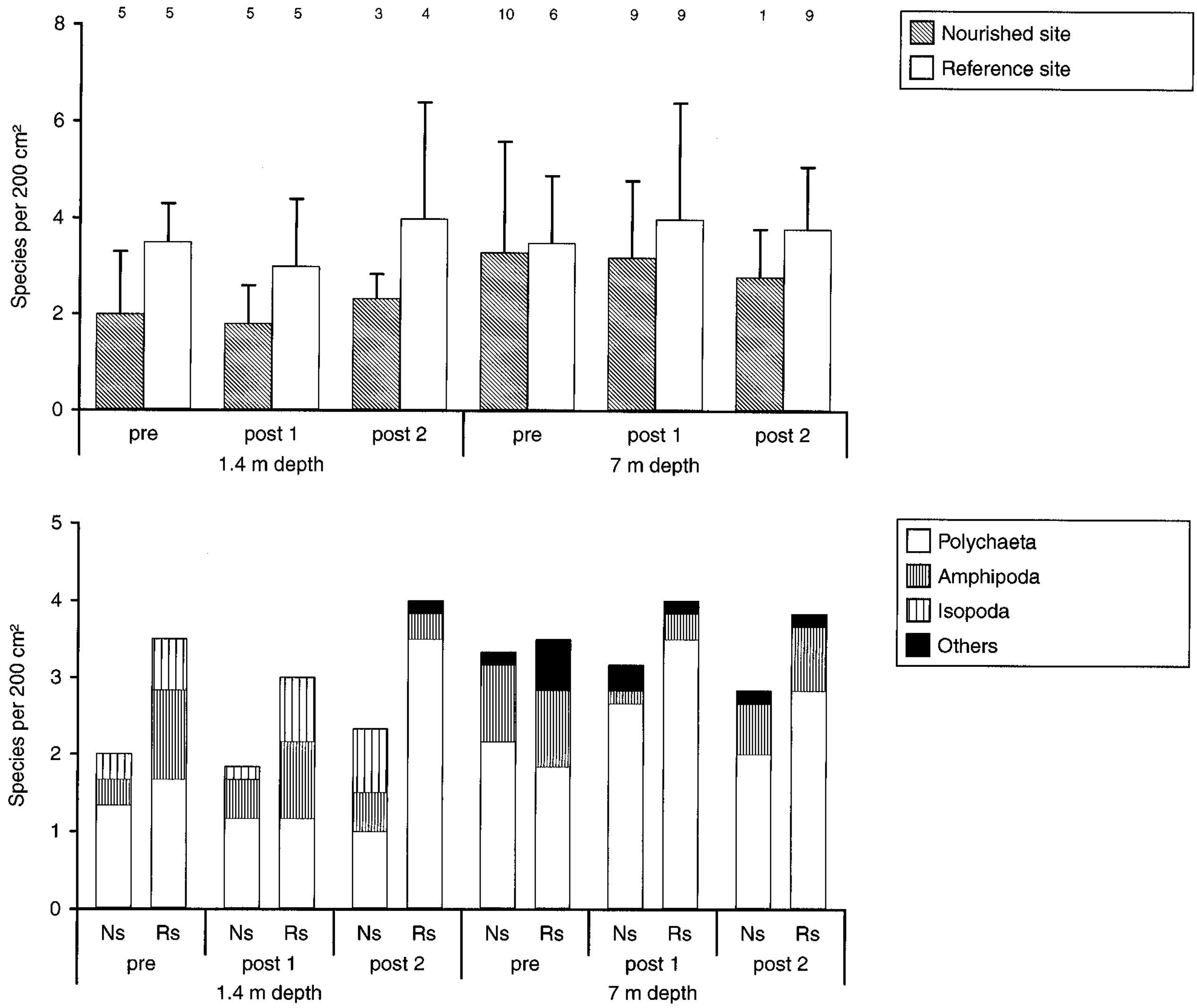


Fig. 12: First nourishment: Comparison of total macrofaunal species density and species density of major taxa per 200 cm² at nourished and reference site at two sampling positions. – Samples taken one month before (= pre, April 1999), three months after (= post 1, October 1999) and nine months after (= post 2, April 2000) the operation. Data given as arithmetic means with standard deviations of 6 replicates per survey. Total numbers of species are shown above each column. Others = nemerteans, decapods and bivalves.

remained in the range of magnitude generally observed between adjacent sites along the beach. It is assumed that most meiofaunal taxa occurring at an intermediate beach type with high wave energy are generally well adapted to shifting sediments and hydrodynamic turbulences (McIntyre 1971; McLachlan et al. 1984; Armonies & Reise 2000; Menn 2002). Meiofauna seems to rapidly recover at the nourished site, presumably because many species are fast reproducing and often are highly mobile, such as the dominant plathelminth *Notocaryoplanella glandulosa* in the intertidal at the Sylt shore. Recovery of meiofauna may depend on both active migration and passive re-suspension into the water column (Palmer 1988; Fegley 1988; Schratzenberger & Thiel 1995; Armonies 1988). It may be further enhanced by the high dynamics of the intermediate beach system.

Schratzenberger & Thiel (1995) also reported minor short-term effects on the meiofauna by a beach nourishment, primarily on copepods (harpacticoids), as shown in this study too.

Effects on the Macrofauna Community

A minor short-term negative impact by the nourishment in 1999 on the macrofauna in the shallow subtidal was indicated by reduced abundances of *Eurydice pulchra* and *Scolelepis squamata* in the first post-nourishment survey, while nine months after the operation no more differences in abundances between nourished and reference site were detected (Tab. 5). The larger nourishment in 2000 revealed a longer-term effect on the macrofauna in the deeper subtidal. Polychaete abundances and species density at 7 m depth were still reduced nine months after the operation. Increasing wave disturbance and sediment transport initiated by the nourishment (Brown & McLachlan 1990; Rakocinski et al. 1996) may directly affect the macrofauna organisms. Also, their recruitment may be affected due to a coincidence of both operations with the reproductive season (see Naylor 1972; A. Rodriguez pers. comm.). The time of the nourishment is

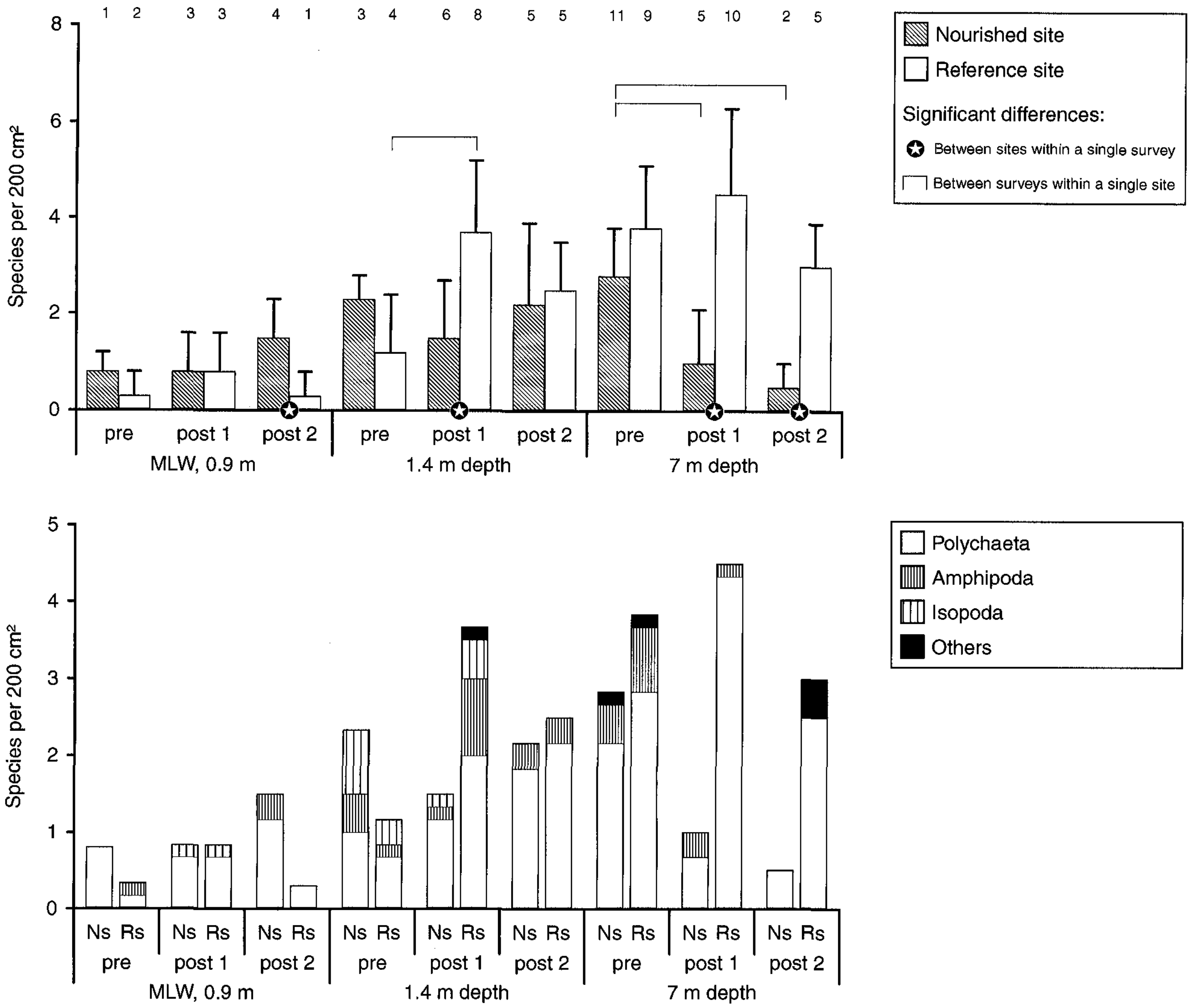


Fig. 13: Second nourishment: Comparison of total macrofaunal species density and species density of major taxa per 200 cm^2 at nourished and reference site at three sampling positions. – Samples taken one month before (= pre, April 2000), four months after (= post 1, October 2000) and nine months after (= post 2, March 2001) the operation. Data given as arithmetic means with standard deviations of 6 replicates per survey. Total numbers of species are shown above each column. Others = decapods and bivalves.

proposed by several authors as an important factor determining the effects of the operation and the duration of the recovery (REILLY & BELLIS 1983; ADRIAANSE & COOSEN 1991; LÖFFLER & COOSEN 1995; ESSINK 1997; PETERSON et al. 2000).

Minor negative effects by beach nourishment on the macrofauna in the lower intertidal and shallow subtidal accompanied by a fairly rapid recovery, as it was shown in 1999, were also reported from other studies in Denmark, Germany, Belgium, The Netherlands and Florida (CULTER & MAHADEVAN 1982; SALOMAN & NAUGHTON 1984; GORZELANY & NELSON 1987; BIRKLUND et al. 1996; LE ROY et al. 1996; RAKOCINSKI et al. 1996; VAN DALFSEN & ESSINK 1997; GROTJAHN & LIEBEZEIT 1997). To some extent, macrofauna at high-energy beaches may be well adapted to rapid morphological changes (NELSON 1993; LÖFFLER & COOSEN 1995). Most of these macrofaunal species are opportunistic, with a short life cycle and a large reproductive potential. As in meiofauna, the organisms are often characterized by a high mobility, which is true for the dominant species at the Sylt beach, *S. squamata* and *E. pulchra.* Such characteristics are important for the recovery, which depends on a recruitment from pelagic larvae or immigration by mobile adults from adjacent sites.

In contrast to the macrofauna in the intertidal and shallow subtidal, the one in the deeper subtidal may have a higher sensitivity to disturbances, which is likely to result from a higher abundance of long-lived species and a higher diversity in the deeper subtidal than in the highly dynamic intertidal communities (MCINTYRE & ELEFTHERIOU 1968; KNOTT et al. 1983; REISE 1985; BROWN & MCLACHLAN 1990; MENN 2002). This is supported by the results of the study in 2000. A greater adverse impact on offshore than on intertidal communities is also assumed by PARR et al. (1978) and RAKOCINSKI et al. (1996). A comparison of the results from both nourishments indicates that the sediment transport initiated by the first one may not have extended down to the 7 m depth contour. A steeper profile after the second and larger nourishment in 2000

Table 7: Statistics of total macrofaunal species density and species density of major taxa per 200 cm² at the nourished site and the reference site for the second nourishment. – * = assumed to indicate a tendency. Square root transformation: 7 m depth post 1 Polychaeta. For occasions of pre- and post-nourishment samplings see Fig. 3.

	One-way ANOVA			
	[p <]	df	F	HSD-Test [p <]
Mean low water				
post 2	0.025	1	8.45	
1.4 m depth				
post 1	0.025	1	7.48	
post 1: Amphipoda	0.025	1	7.35	
Reference site: pre / post 1	0.01	3	5.95	0.01
Reference site pre / post 1: Amphipoda	0.01	3	4.20	0.03*
7 m depth				
post 1: Total	0.01	1	17.09	
post 1: Polychaeta	0.001	1	26.04	
post 2: Total	0.001	1	34.09	
post 2: Polychaeta	0.001	1	40.00	
Nourished site Total pre / post 1	0.001	3	11.01	0.01
Nourished site total: pre / post 2	0.001	3	11.01	0.01
Nourished site pre / post 1: Polychaeta	0.01	3	9.89	0.01
Nourished site pre / post 2: Polychaeta	0.01	3	9.89	0.01

made beach morphometries more reflective than in 1999. This may have increased wave disturbance and sediment transport, as it is reported by Brown & McLachlan (1990). Ahrendt (1994) also reported sediment transport dynamics down to about 7 m depth by a nourishment at the Sylt shore.

The temporary decline of polychaetes after the larger operation in 2000 may have affected subtidal consumers. However, considering the spatial extension of the subtidal offshore habitat, this may have no overall significance. Moderate effects of beach nourishment on migrating consumers are also reported in other studies (Löffler & Coosen 1995; van Dalfsen & Essink 1997). However, harmful consequences may be observed in shores with higher secondary production than at Sylt, due to a reduced energy transfer to higher trophic levels (Reilly & Bellis 1983; van Dalfsen & Essink 1997; Petersen et al. 2000).

The Match of Grain Size

Grain size of the nourished material is considered by several authors as an important factor determining the effects of beach nourishment on the macrofauna (e.g. Hayden & Dolan 1974; Nelson 1993; Löffler & Coosen 1995; Peterson et al. 2000). Sediment composition is also often mentioned as one factor determining the meiofauna (Jansson 1967; Gray & Rieger 1971; Gray 1974; Giere 1993). The results of the grain size analyses of both nourishment operations indicate a good match of grain sizes between the replenished material and the shore sediment. Only at mean low water, grain size differed three months after both operations. However, no negative impact on the infauna was noticed at this position, while the infauna was affected in the subtidal despite of a good match of grain size. Similar results were reported by Rakocinski et al. (1996). Thus, a good match of grain size may enhance a rapid recovery of the infauna, but it may not be the key to determine the impact on the biota.

Effects of Recurrent Nourishments

A comparison of the infauna after both nourishments revealed a lower macrofaunal abundance at 1.4 m depth and reduced meiofaunal abundances and species densities of plathelminths and polychaetes at the four transect positions in October 2000 compared with October 1999 (Tab. 8). These differences in infauna composition were also noticed by a comparison between the results of 2000 and those of an earlier investigation in 1998 at the same beach (Menn 2002). This may be interpreted as a year-by-year variability rather than a long-term effect of the two-fold beach nourishment, because the differences in the infauna between the surveys occurred at the nourished and the reference site alike. Additionally, the survey in 1999 indicates a complete recovery before the operation in 2000 began. If the recovery is not complete before the next nourishment begins at the same site, larger and longer-term effects are to be expected. In contrast to the study in 1999/2000, the one in 2000/2001 showed no recovery of the macrofauna until nine months after the operation. Van Dalfsen & Essink (1997) reported a recovery of the macrofauna within 1-2 years after a shoreface nourishment. It is therefore recommended to replenish a given site at intervals no shorter than three years to allow the macrobenthos to recover sufficiently.

Effects of Different Nourishment Operations

Beach nourishment operations require relatively calm weather conditions, which tend to be limited to the summer

Table 8: Comparison of the infauna between the studies in 1999/2000 and an earlier study in 1998. – Presented are significant differences of total macrofaunal abundance per 200 cm^2 and of total meiofaunal abundance and species density per 10 cm^2 between the sampling in October 1999 and 2000, and between the October surveys in 1998 and 2000. Wilcoxon's non parametric U-Test (degree of freedom = 1) was used to test for differences. Significance was assumed at $p < 0.05$.

		1999	2000	1998	1999/2000	1998/2000
Macrofauna abundance						
1.4 m depth	Nourished site	18 ± 9	4 ± 4	49 ± 27	0.01	0.01
	Reference site	38 ± 15	16 ± 12	49 ± 27	0.025	0.025
Meiofauna abundance						
Mid shore	Nourished site	311 ± 77	72 ± 61	522 ± 137	0.01	0.01
	Reference site	455 ± 115	138 ± 105	522 ± 137	0.01	0.01
Mean low water	Nourished site	726 ± 103	30 ± 47	517 ± 224	0.01	0.01
	Reference site	654 ± 217	167 ± 178	517 ± 224	0.01	0.025
1.4 m depth	Nourished site	282 ± 167	10 ± 6	194 ± 62	0.01	0.01
	Reference site	233 ± 94	86 ± 71	194 ± 62	0.025	0.01
7 m depth	Nourished site	206 ± 198	9 ± 11	161 ± 110	0.01	0.01
	Reference site	334 ± 125	6 ± 8	161 ± 110	0.01	0.01
Meiofauna species density						
Mid shore	Nourished site	2 ± 0	2 ± 1	6 ± 1	0.01	0.01
	Reference site	5 ± 8	4 ± 1	6 ± 1	–	0.01
Mean low water	Nourished site	3 ± 1	2 ± 1	7 ± 2	0.01	0.01
	Reference site	3 ± 1	4 ± 2	7 ± 2	0.01	0.01
1.4 m depth	Nourished site	2 ± 0	2 ± 1	5 ± 1	0.01	0.01
	Reference site	3 ± 1	1 ± 1	5 ± 1	0.01	0.01
7 m depth	Nourished site	1 ± 0	1 ± 1	4 ± 2	0.05	0.01
	Reference site	0 ± 0	1 ± 1	4 ± 2	–	0.025

season. This may therefore interfere with recruitment of the benthos in spring and summer. However, important effects on the beach system will occur only if replenishments are performed all at once along the entire beach of an island, which is rather unlikely to take place at an island as long (40 km) as Sylt.

Van Dalfsen & Essink (1997) proposed shoreface nourishment as an alternative to beach nourishment. This could be done outside the recruitment and recreational season. The authors reported relatively small effects on the macrobenthos with a recovery after 1-2 years. However, shoreface nourishment may be less effective at Sylt due to high hydrodynamics at the in- and foreshore regions as a result of a steep offshore profile (K. Ahrendt, Geomar Kiel pers. comm.). This may also prevent a realization of nourishment outside calm weather conditions in summer. Furthermore, the results of this study indicate a high sensitivity of the subtidal benthos, which may be more affected by shoreface nourishment than by beach nourishment. In contrast to beach and shoreface nourishments, draining the beach as an alternative way of beach protection, as it is conducted in Denmark (Danish Geotechnical Institute 2001), may result in large negative effects on the infauna. Especially the meiofauna, which occurs in high abundances in the intertidal, may be negatively affected by dewatering of the beach at low tide. However, a respective investigation has not yet been done.

Conclusion

In conclusion it can be said that the beach nourishments in 1999 and 2000 at Sylt had no dramatic, long-lasting effects on the infauna at the shore, and, from an ecological perspective, they may be regarded as an acceptable method of coastal protection. The meiofauna is generally less affected by such operations than the macrofauna. Nourishments on a larger scale than the operation in 2000 may become critical for the benthos at the deeper subtidal zone adjacent to the beach. Different results were found in other impact studies indicating the requirement for site-specific investigations.

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References

ADRIAANSE, L. A. & COOSEN, J. (1991): Beach and dune nourishment and environmental aspects. – Coast. Eng., **16**: 129-146.

AHRENDT, K. (1994): Geologie und Küstenschutz am Beispiel Sylt. – Ber. Forschungs- und Technologiezentrum Westküste Univ. Kiel., **4**: 136 pp.; Kiel.

ARMONIES, W. (1988): Active emergence of meiofauna from intertidal sediment. – Mar. Ecol. Prog. Ser., **43**: 151-159.

ARMONIES, W. & REISE, K. (2000): Faunal diversity across a sandy shore. – Mar. Ecol. Prog. Ser., **196**: 49-57.

BIRKLUND, J. & TOXVIG, H. & LAUSTRUP, C. (1996): RIACON Evaluation of the nourishment and sand extraction of Torsminde Denmark. – The Danish Coastal Authority in cooperation with the VKI, Draft Final Rep.: 65 pp.

BROWN, A. C. & MCLACHLAN, A. (1990): Ecology of Sandy Shores – 328 pp.; Amsterdam (Elsevier).

BUCHANAN, J. B. (1984): Sediment analysis. – In: HOLME, N. A. & MCINTYRE, A. D. [Eds.]: Methods for the Study of Marine Benthos: 41-65; Oxford (Blackwell).

CHARLIER, R. H. & MEYER, C. P. DE (1995): Beach nourishment as an efficient coastal protection. – Environ. Manage. Health, **6** (5): 26-34.

COOPER, N. J. (1998): Assessment and prediction of Poole Bay (UK) sand replenishment schemes: application of data to Führböter and Verhagen models. – J. Coast. Res., **14** (1): 353-359.

CULTER, J. K. & MAHADEVAN, S. (1982): Long-term effects of beach nourishment on the benthic fauna of Panama City Beach, Florida. – Miscellaneous Rep., **82-2**: 94 pp.; Fort Belvoir.

DALFSEN, J. A. VAN & ESSINK, K. (1997): Risk analysis of coastal nourishment techniques, National Evaluation Report (The Netherlands). – RIKZ Rep., **97.022**: 98 pp.; Haren (Nat. Inst. Coastal and Mar. Manage.).

DETTE, H. H. & GÄRTNER, J. (1987): Erfahrungen mit der Versuchsvorspülung vor Hörnum im Jahre 1983. – Die Küste, **45**: 209-258.

ESSINK, K. (1997): Risk analysis of coastal nourishment techniques RIACON Final evaluation report. – RIKZ Rep., **97.031**: 42 pp.; Haren (Nat. Inst. Coastal and Mar. Manage.).

FEGLEY, S. R. (1988): A comparison of meiofaunal settlement onto the sediment surface and recolonization of defaunated sandy sediment. – J. Exp. Mar. Biol. Ecol., **123**: 97-113.

GIERE, O. (1993): Meiobenthology. – 328 pp.; Berlin, Heidelberg, New York (Springer).

GORZELANY, J. F. & NELSON, W. G. (1987): The effects of beach replenishment on the benthos of a sub-tropical Florida beach. – Mar. Environ. Res., **21**: 75-94.

GRAY, J. S. (1974): Animal-sediment relationship. – Oceanogr. Mar. Biol. Ann. Rev., **12**: 223-261.

GRAY, J. S. (1981): The ecology of marine sediments. An introduction to the structure and function of benthic communities. – Cambridge Studies in Modern Biology, **2**; Cambridge (Cambridge University Press).

GRAY, J. S. & RIEGER, R. M. (1971): A quantitative study of the meiofauna of an exposed sandy beach, at Robin Hood's Bay, Yorkshire. – J. Mar. Biol. Ass. U.K., **51**: 1-19.

GROTJAHN, M. & LIEBEZEIT, G. (1997): Risk of beach nourishment for the foreshore and shallow shoreface benthic communities on the island of Norderney, Germany. Evaluation of the nourishment in 1994. – Risk Analysis of coastal Nourishment Techniques (RIACON) Nat. evaluation Rep. (Germany): 34 pp.; Norden, Wilhelmshaven (Aqua-Marin, TERRAMARE)

HAYDEN, B. & DOLAN, R. (1974): Impact of beach nourishment on distribution of *Emerita talpoida*, the common mole crab. – J. Waterways, Harbors Coast. Eng. Div. ASCE, **10538** (WW2): 123-132.

JANSSON, B.-O. (1967): The significance of grain size and pore water content for the interstitial fauna of sandy beaches. – Oikos, **18**: 311-322.

KNOTT, D. M. & CALDER, D. R. & DOLAH, R. F. VAN (1983): Macrobenthos of sandy beach and nearshore environments at Murrells Inlet, South Carolina, USA. – Est. Coast. Shelf Sci., **16**: 573-590.

LE ROY, D. & DEGRAER, S. & MEGAERT, K. & DOBBELAERE, I. & VINCX, M. & VANHAECKE, P. (1996): Risk of shoreface nourishment for the coastal marine benthic community. Evaluation of the nourishment of De Haan, Belgium. – ECOLAS N.V., Antwerpen.

LEATHERMAN, S. P. (1987): Beach and shoreface response to sea-level rise: Ocean City, Maryland, U.S.A. – Prog. Oceanog., **18**: 139-149.

LÖFFLER, M. & COOSEN, J. (1995): Ecological impact of sand replenishment. – In: HEALY, M. G. & DOODY, J. P. [Eds.]: Directions in European Coastal Management: 291-299; Cardigan (Samara Publishing).

LOZÁN, J. L. & GRAßL, H. & HUPFER, P. (2001): Climate of the 21st Century: Changes and Risks. – 448 pp.; Hamburg (Wiss. Auswertungen).

MCINTYRE, A. D. (1971): Control factors on meiofauna populations. – Thalassia Jugoslavica, 7 (1): 209-215.

MCINTYRE, A. D. & ELEFTHERIOU, A. (1968): The bottom fauna of a flatfish nursery ground. – J. Mar. Biol. Ass. U.K., **48**: 113-142.

MCLACHLAN, A. & COCKCROFT, A. C. & MALAN, D. E. (1984): Benthic faunal response to a high energy gradient. – Mar. Ecol. Prog. Ser., **16**: 51-63.

MENN, I. (2002) Ecological comparison of two sandy shores with different morphodynamics in the North Sea. – Rep. Polar and Mar. Res., **417**: 170 pp.

NAYLOR, R. (1972): British Marine Isopods. – 85 pp., London, New York (Academic Press).

NELSON, W. G. (1993): Beach restoration in the southeastern US: environmental effects and biological monitoring. – Ocean Coast. Manage., **19**: 157-182.

NELSON, D. A. & PULLEN, E. J. (1985): Environmental considerations in using beach nourishment for erosion protection. – In: Using Beach Nourishment for Erosion Protection. – Proc. 2nd Water Quality and Wetlands Conf.; New Orleans.

NOLDT, U. & WEHRENBERG, C. (1984): Quantitative extraction of living plathelminthes from marine sands. – Mar. Ecol. Prog. Ser., **20**: 193-201.

NORDSTROM, K. F. (2000): Beaches and Dunes of Developed Coasts. – 338 pp.; Cambridge (Cambridge University Press).

PALMER, M. A. (1988): Dispersal of marine meiofauna: a review and conceptual model explaining passive transport and active emergence with implications for recruitment. – Mar. Ecol. Prog. Ser., **48**: 81-91.

PARR, T. & DIENER, D. & LACY, S. (1978): Effects of beach replenishment on the nearshore sand fauna at Imperial Beach, California. – Miscellaneous Rep., **78-4**: 125 pp.; Fort Belvoir.

PETERSON, C. H. & HICKERSON, D. H. M. & JOHNSON, G. G. (2000): Short-term consequences of nourishment and bulldozing on the dominant large invertebrates of a sandy beach. – J. Coast. Res., **12** (2): 368-378.

PILKEY, O. H. & WRIGHT, H. L. (1989): Seawalls versus beaches. – In: KRAUSS, N. C. & PILKEY, O. H. [Eds.]: The effects of seawalls on beaches. – J. Coast. Res., **SI 4**: 41-67.

RAKOCINSKI, C. F. & HEARD, R. W. & LECROY, S. E. & MCLELLAND, J. A. & SIMONS, T. (1996): Responses by macrobenthic assemblages to extensive beach restoration. – J. Coast. Res., **12** (1): 326-353.

REILLY, F. J. Jr. & BELLIS, V. J. (1983): The ecological impact of beach nourishment with dredged materials on the intertidal zone at Bogue Banks, North Carolina. – Miscellaneous Rep., **83-3**: 73 pp., Fort Belvoir.

REISE, K. (1985): Tidal Flat Ecology. – 191 pp.; Berlin, Heidelberg, New York (Springer).

SACHS, L. (1984): Angewandte Statistik. – 550 pp.; Berlin, Heidelberg, New York (Springer).

SALOMAN, C. H. & NAUGHTON, S. P. (1984): Beach restoration with offshore dredged sand: effects on nearshore macrofauna. – NOAA Techn. Mem. NMFS-SEFC, **133**: 20 pp.; Panama City.

SCHMIDT, P. (1968): Die quantitative Verteilung und Populationsdynamik des Mesopsammons am Gezeiten-Sandstrand der Nordseeinsel Sylt I. Faktorengefüge und biologische Gliederung des Lebensraumes. – Int. Rev. Ges. Hydrobiol., **53** (5): 723-779.

SCHRATZENBERGER, M. & THIEL, H. (1995): Ökologische Auswirkungen von Sandvorspülungen auf die Strandfauna. – Die Küste, **57**: 47-64.

SHORT, A. D. (1999): Handbook of Beach and Shoreface Morphodynamcis. – 379 pp.; Chichester (Wiley & Sons).

SHORT, A. D. & WRIGHT, L. D. (1983): Physical variability of sandy beaches. – In: MCLACHLAN, A. & ERASMUS, T. [Eds.]: Sandy Beaches as Ecosystems: 133-144; The Hague (W. Junk).

SOKAL, R. R. & ROHLF, F. J. (1995): Biometry. – 887 pp.; New York (Freeman).

VALVERDE, H. R. & TREMBANIS, A. C. & PILKEY, O. H. (1999): Summary of beach nourishment episodes on the U.S. east coast barrier islands. – J. Coast. Res., **15** (4): 1100-1118.

WALTON, T. L. & SENSABAUGH, W. M. (1979): Seawall design on the open coast. – Florida Grant Rep., **29**: 24 pp.

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