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Impacts of sedimentation on soft-bottom benthic communities in the southern islands of Singapore

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Abstract

Benthic community data from eight stations around Pulau Semakau, an island south of Singapore, were collected during three surveys and analysed to determine changes in community structure under different sediment regimes resulting from construction activity at the eastern part of Pulau Semakau. Multidimensional Scaling (MDS) Configurations indicated distinct changes in the abundance, family number and diversity of benthic invertebrate fauna, which corresponded to sedimentation rate. SIMPER analysis suggested that polychaetes tolerate increased sedimentation better than crustaceans and molluscs. Sedimentation rate and other physico-chemical parameters were also investigated to determine the relationship between environmental factors and benthic community structure. Results from Principal Component Analysis (PCA) showed that sedimentation rate, sediment composition and ammonia concentration were the most important factors impacting the benthic community.

Introduction

Human activities such as the dumping of earth spoils, land reclamation and commercial fishing have impacted marine ecosystems seriously in recent years. Some of these impacts are increased sedimentation, changes in physical and chemical parameters of the marine system, and disturbances in biology communities. The study of benthic communities is a particularly useful and sensitive tool for identifying sediment-related stress (Alongi, 1990). The analysis of changes in benthic community structure has now become one of the main methods of detecting and monitoring the biological effects of marine disturbance. Many studies have been made on the impacts of pollution resulting from human activities on benthic communities (Nicolaidou et al., 1989; Hall et al., 1990, 1992; Olsgard & Hasle 1993; Hatcher et al., 1994).

Pulau Semakau is situated south of mainland Singapore (Fig. 1), and was surrounded by large areas of patch reefs and an extensive fringing reef. Dumping of earth spoils started in 1988 to convert the eastern sea of the island into a landfill site (Anonymous, 1989; Liu, 1989). An extensive bund to connect Pulau Semakau and neighbouring Pulau Sakeng to enclose the sub-marine landfill site was constructed and sediment screens were placed to prevent the spread of sediment after 1995 (Nathan, 1993, 1995).

This study aims to describe the impacts from this construction activity by examining the changes in the structure of the soft-bottom communities with regard to environmental changes in space and time. Ambient physical-chemical parameters were monitored and the nutrient analysis in this study focused on ammonium, nitrate, nitrate, nitrite concentration and organic-inorganic ratio in benthic water, bottom sediment and input sediment.

Multidimesional Scaling (MDS) was used to analyse the soft-bottom benthic community by ordination to identify changes in the community over space and time. One-way ANOVA and correlation coefficient were also employed to determine significant deviations among stations and the relationship between community and environment factors.

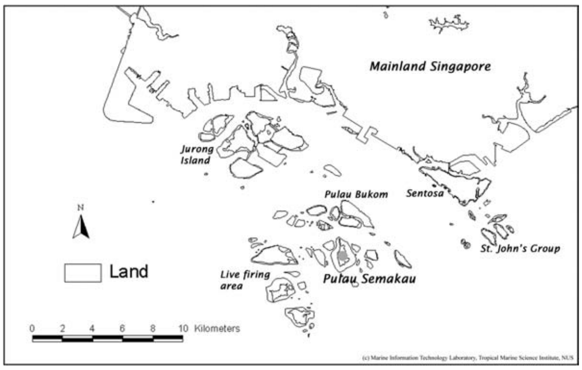


Figure 1. Map of the Southern Islands of Singapore.

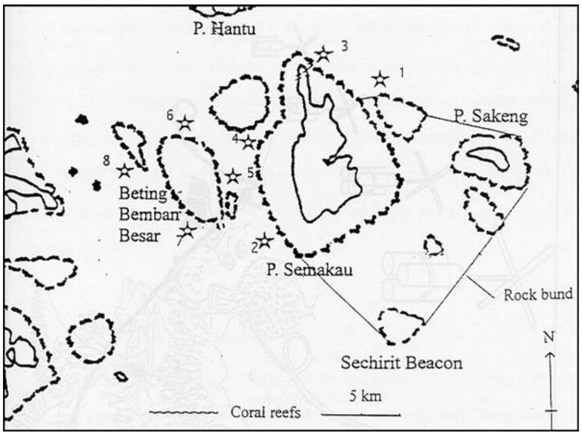


Figure 2. Map of Pulau Semakau showing survey stations.

Materials and methods

A total of 8 stations with soft-bottom areas were surveyed in June 1996, December 1996 and May 1997 around Pulau Semakau (Fig. 2). These 8 stations ranged from sites close to the rock bund construction (stations 1 and 2) to sites further away from construction activities (stations 7 and 8).

Five grab samples were taken at each station using the Smith-McIntyre grab. The contents were stored in 10% formalin and sorted for fauna using 1mm sieves. One bottle of sediment was collected and stored at −20 °C for nutrient and grain size analyses. Water samples were taken only near the sea bottom.

Sedimentation rate was measured using sediment traps (5 cm diameter, 11.5 cm height) placed 20 cm above the seabed. Three traps were tied together on a stainless steel rod as one replicate. Four replicates were set at 1m intervals at each station (English et al., 1994). Traps were collected three weeks after setting them down. Trap contents, including all suspended particles, were filtered using Whatman 42 filter papers which were then dried at 65 °C for 24 h and weighed (Novitsky, 1990).

Six environmental parameters (turbidity, salinity, pH, conductivity, dissolved oxygen and light intensity) were measured at the maximum depth of each station for each survey. Turbidity and light intensity were measured using a LI-COR underwater light sensor. The YSI model 33 Salinity-Conductivity-Temperature Meter was used to measure salinity and temperature. Dissolved oxygen levels were obtained *in situ* using a portable YSI model 57 Oxygen Meter. The conductivity of the water was measured using a pHOX 52E Conductivity Meter, while bottom pH was measured with an Orion portable pH meter Model SA 250 from water samples collected by SCUBA divers.

The analysis for sediment particle size (Buchanan, 1984) was carried on three replicates from the upper 2 cm layer of sediment. Small stones and shells were removed before drying, and the residue was sieved on a mechanical sieve shaker through 6 sieves (mesh sizes from 0.063–2 mm) for 30 min. Thereafter, the sediment present in each sieve was weighed.

Ammonium, nitrate and nitrite were extracted from dried sediment samples using a 36% sodium chloride solution (Beckett et al., 1992; Hatcher et al., 1994). Water samples and sediment extracts were filtered through Whatman 42 filters and 1 ml l^{-1} of 6N sulphuric acid was added into the samples for preservation. Water samples were then stored at −20 °C, and nutrient concentrations in all samples were measured using Flow Injection Analyser (FIA). Three 3 mg subsamples were also taken from dried samples and treated at 580 °C overnight. The ash remaining in the crucible was considered the inorganic portion of the sample.

The animals sieved from grab contents were fixed in a 10% formalin solution overnight, then stored in 70% ethanol solution. All animals were identified to family level (Warwick, 1988; Warwick & Clarke, 1991) with the exception of amphipods and isopods, which could only be identified to Order.

For each replicate and each station, community diversity was measured by the Shannon–Weaver diversity index H', defined as $H' = -\Sigma p_i \log_2 p_i$, where p_i is the proportion of the ith family in the population. ANOVA was then used to test significant differences in diversity across stations and times.

Data were represented graphically using Multidimensional Scaling (MDS), a non-parametric multivariate statistical ordination method (Kruskal &

Wish, 1978; Clarke & Ainsworth, 1993). MDS was applied to non-standardised data, with double square root transformations of abundances to analyse the community differences across stations. As sample size in this study was small, the total abundance of families was used to indicate an overall trend in space and time (Kroncke et al., 1992; Kroncke & Rachor, 1992).

The significance of faunistic difference among stations was determined using the ANOSIM randomisation test (Clarke & Green, 1988). Following the division into groups from the ordination analysis, families having the greatest contribution to this division were determined using the similarity percentages programme SIMPER (Warwick et al., 1990).

Relationships between community structure and environmental variables were studied using Principal Component Analysis (PCA) to determine which variables contribute most to differences in community structure.

Results

Sedimentation rates

Sedimentation rates around Pulau Semakau ranged from 0.00436 g cm^{-2} d^{-1} (station 4) to 0.0836 g d^{-1} cm^{-2} (station 1) (Fig. 3). The sedimentation rates were significantly different among the eight stations (one-way ANOVA, $df = 7$, $F = 9.454$, $p < 0.001$). Stations 1 and 2 had the highest sedimentation rate. Stations 6 and 7 were further from the construction area than stations 1, 2 and 3, and had the lowest sedimentation rates. Station 8 was the furthest from the construction area but had relatively high sedimentation rates. This might be due to the effect of water currents.

The stations did not exhibit large changes in average sedimentation rate over the 3 survey periods except for station 4 (Fig. 3). One-way ANOVA confirmed that there were no significant differences among the three surveys (one-way ANOVA, $df = 2$, $F = 0.482$, $p = 0.624$). Station 4, which was next to a big coral reef patch, had the lowest sedimentation rate during the first survey. Subsequently, a drain was built on the island to remove the water and silt from the construction area. As a result, the sedimentation rate at station 4 increased more than tenfold from 0.00436 to 0.0641 g cm^{-2} d^{-1} and remained unchanged during the third survey. Station 5, which was near station 4, showed a similar trend. Sedimentation rates increased slightly at stations 1 and 8, but decreased at stations 3 and 6, and remained steady throughout the surveys at station 7.

Environmental parameters

Sediment particles with sizes from 63 to 500 μm were grouped in the fine to medium sand fraction while those from 0.5 to 2 mm were categorised as coarse sand. Silt/clay fraction indicates particles with sizes less than 63 μm. Silt/clay (<63 μm) and fine sand (63–500 μm) were dominant at all stations. The majority of the sediment samples had higher proportions of the silt/clay fraction compared to undisturbed areas (Fig. 4). There were significant differences among the eight stations during the three surveys (One-way ANOVA, $df = 7$, $F = 7.302$, $p < 0.001$). Stations 1, 2 and 3 had very high silt and clay fractions (47%, 44% and 36%, respectively, at the first survey), while stations 5, 6 and 7 had relatively less silt/clay fractions ranging from 7% to 9%. Station 8 had the median silt/clay level (17%) among the eight stations. No significant differences among the three surveys for each station (One way ANOVA, $df = 2$, $F = 1.297$, $p < 0.302$), although an obvious change was observed in the sediment particle size between the first two surveys and the third survey at stations 4 and 6. The silt/clay fraction at station 4 increased from 22.5% at the first survey to 59.7% at the third survey, and from 10% to 34.8% for station 6. This change is similar to the sedimentation rate change mentioned previously and could be due to the construction of the drain on the island after the first survey period.

The ratios of organic to inorganic (O/I) matter of bottom and trap sediment were also compared (Fig. 5). Organic matter occupied 4% to 10% of all the sediment. O/I ranged from 0.07 to 0.13 in trap sediment and from 0.03 to 0.14 in the bottom sediment. O/I in trap and seabed had significant differences among the stations (One-way ANOVA, $df = 7$, $F = 2.807$, $p = 0.017$). The stations (1, 2, 3, 4, 5) near the construction area yielded low O/I for both trap and bottom sediment. Stations 6, 7 and 8 had comparatively higher organic matter input and more organic matter in the sediment. Among all the stations (except station 2 in the first survey, stations 6 and 7 at second survey), the O/I in trap sediment, which indicates the sediment input, were higher than bottom sediment.

Concentrations of ammonium (NH_4^+) were measured in bottom water, bottom sediment and trap sediment (Fig. 6). The average levels for all stations in three surveys ranged from 0.007 mg l^{-1}

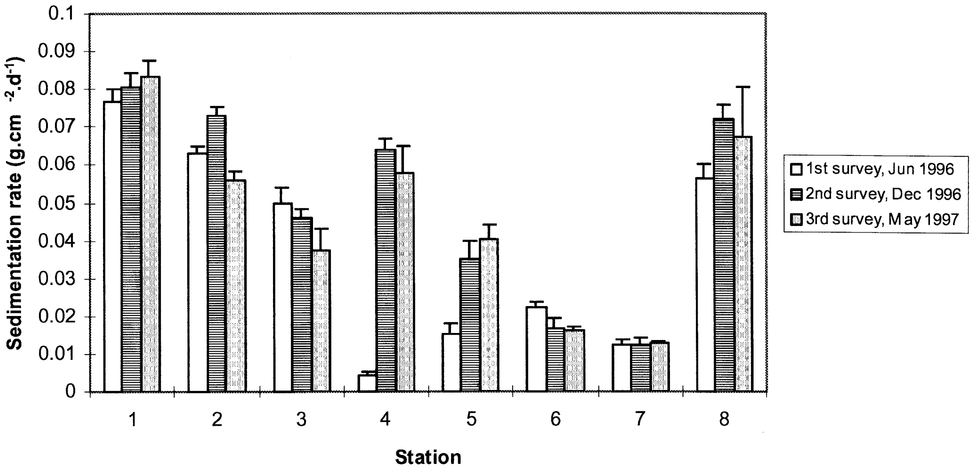


Figure 3. Temporal variation in sedimentation rates at eight stations around Pulau Semakau.

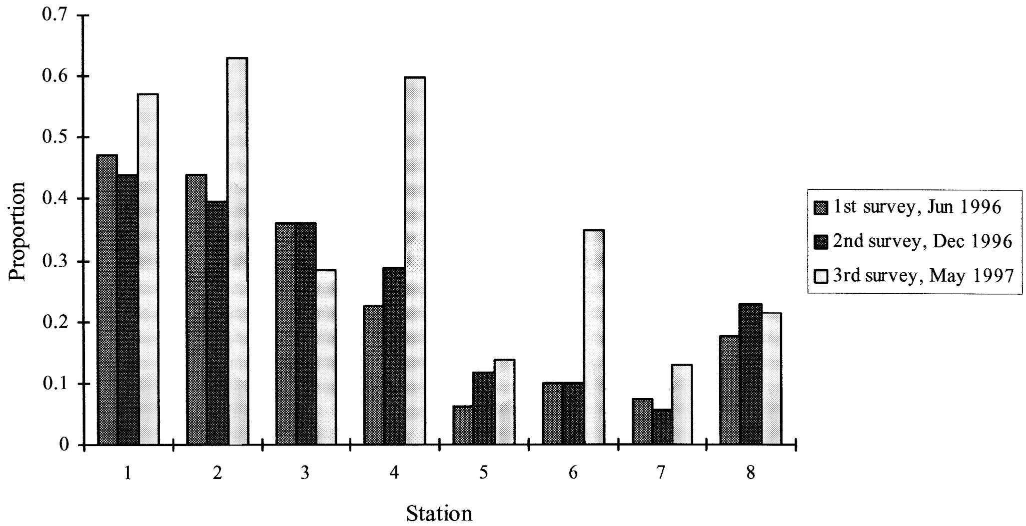


Figure 4. The proportion of silt/clay fraction in the sediment from eight stations around Pulau Semakau during the three surveys.

to 0.182 mg l^{-1} in water and 0.008 mg g^{-1} to 0.042 mg g^{-1} in sediment from bottom and trap. The sediment NH_4^+ concentration (One-way ANOVA, $df = 7$, $F = 5.113$, $p = 0.003$) and trap NH_4 concentration (One-way ANOVA, $df = 7$, $F = 4.174$, $p = 0.0085$) were significantly different among stations. However, the NH_4^+ concentration in water did not have significant differences among eight stations.

High NH_4^+ input did not always result in high NH_4^+ in sediment (Fig. 6). When there was high NH_4^+ concentration in water, there was less NH_4^+ concentration in the bottom sediment at most of the stations. The bottom sediment had slightly higher NH_4^+ concentration than in water at stations 4 (second survey) and 5 (first survey). Nitrate and nitrite concentrations were less than 0.001 mg l^{-1} at all stations, which were too low to detect for comparison, and thus were omitted from the study.

Physico-chemical parameters of each station were measured *in situ* during three surveys (Table 1). Water temperatures remained fairly constant at all the stations with a mean of 29.8 °C. Dissolved oxygen content varied from 4.85 to 5.98 ppm, and conductivity varied little with respect to time. Water salinity varied from 24.5 to 30.2‰ and was generally lower at the stations near the construction site. Light intensity dropped rapidly close to the construction area and ranged from 9.36E+01 to 1.07E+1 μmol m^{-2} sec^{-1} at all stations.

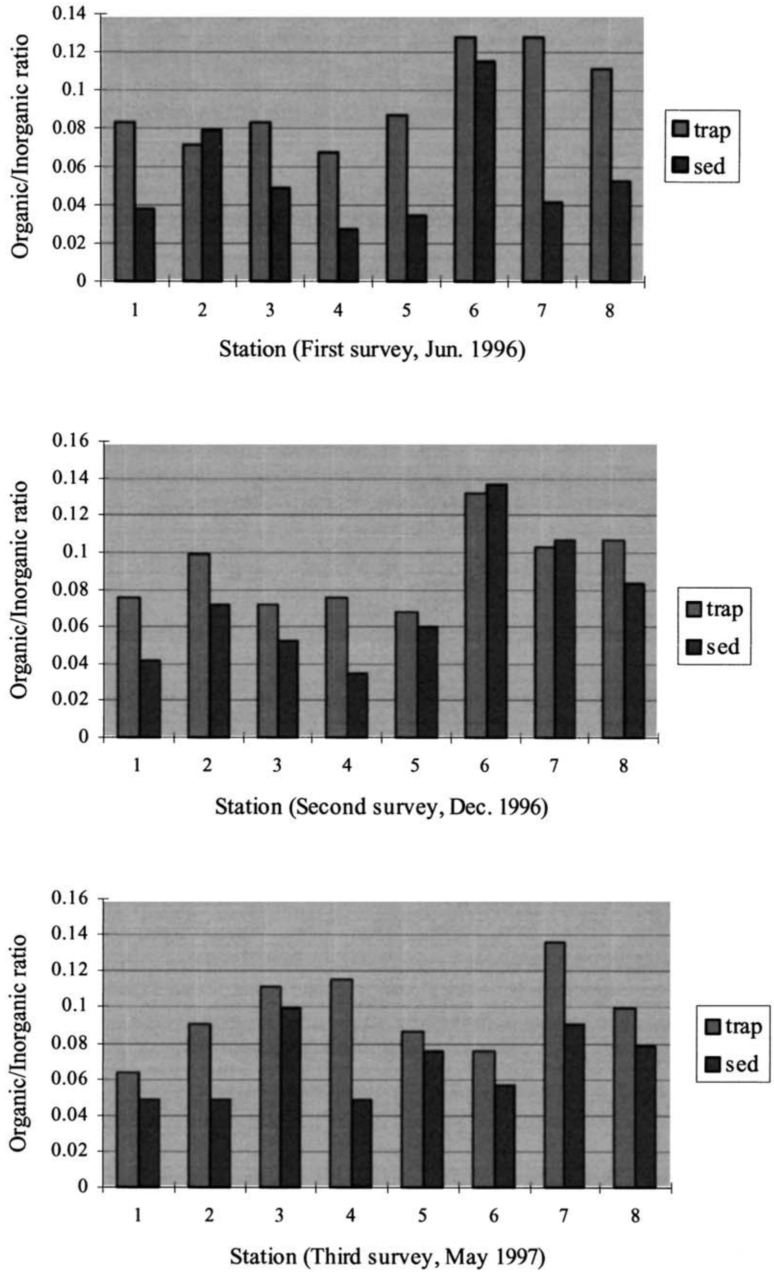


Figure 5. Organic/Inorganic ratio of sediment from seabed and sedimentation trap of eight stations in three surveys (trap: sediment samples from trap, sed: sediment samples from seabed).

Sedimentation rates and silt/clay percentage were shown to be significantly correlated ($r = 0.680$, $p < 0.001$) (Table 2). The increased sedimentation added finer particles to the benthic layer. Positive correlation was observed between the ratio of organic/inorganic matter in sediment from seabed and traps, as well as between organic/inorganic ratio and NH_4^+ concentration in trap, sediment, and water. Sedimentation rate and NH_4^+ concentration in water, and silt/clay percentage and NH_4^+ concentration in water were all negatively correlated. NH_4^+ concentration in water is inversely related to that in bottom sediment.

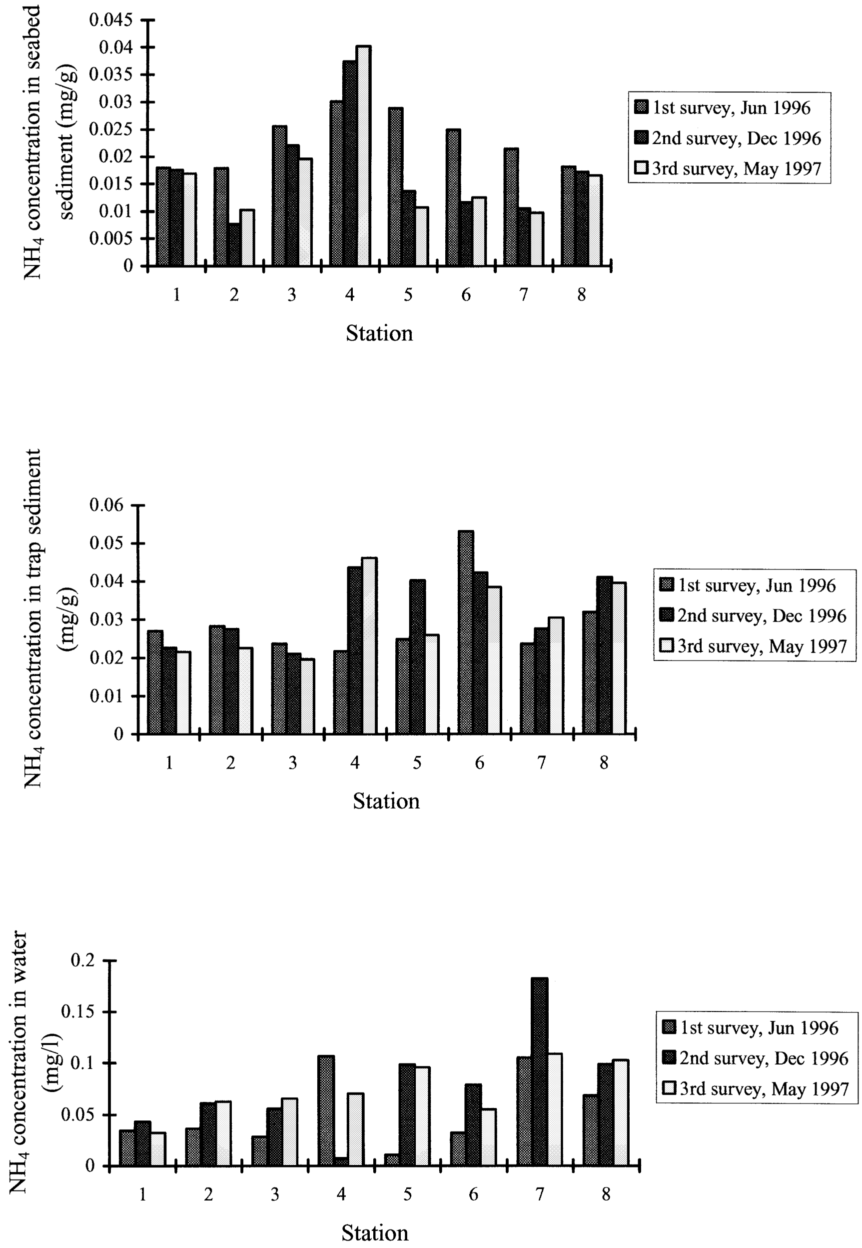


Figure 6. Ammonium concentration ($NH4^+$) in samples of sediment from seabed, traps, and in water from eight stations in three surveys.

Benthic fauna

A total of 735 specimens belonging to 37 families in five phyla were identified from the three surveys. Faunal abundance (Fig. 7), biomass (Fig. 8) and diversity (Fig. 9) were measured at all eight stations. Due to low density of benthic fauna and high variance in grab samples, data were pooled from the five grabs at each station to give a better representative of each station. There were significant differences in total abundances among the eight stations (One-way ANOVA, $df = 6$, $F = 3.243$, $p = 0.0243$). Total abundance of infaunal invertebrates was higher at stations 5, 6 and 7 which were far away from the construction area. Station 7 yielded the highest abundance of 81 individuals during the second survey. Stations 1, 2 and 3 which were near the construction area had lower abundances (5 to 28 individuals) than

Table 1. In situ physical and chemical parameters at eight stations of Pulau Semakau over three surveys

	Station	Temperature (°C)	Dissolved oxygen (ppm)	Conductivity (μS)	Salinity (‰)	Light intensity (μmol m^{-2} s^{-1})
1st survey						
	1	30.2	5.17	4.7	24.5	2.04E+01
	2	29.8	5.72	4.8	30.1	2.24E+01
	3	29.6	5.04	4.75	30.0	3.15E+01
	4	30.0	5.24	4.85	29.6	5.89E+01
	5	30.1	5.91	4.9	26.5	6.15E+01
	6	29.8	5.98	4.75	27.3	6.60E+01
	7	30.2	5.96	4.8	30.1	7.92E+01
	8	30.1	5.76	4.85	26.4	3.55E+01
2nd survey						
	1	29.9	5.01	4.75	25.8	2.15E+01
	2	30.1	5.34	4.95	26.3	2.05E+01
	3	29.4	5.21	4.65	26.4	2.93E+01
	4	30.0	4.85	4.75	30.8	1.07E+01
	5	29.9	5.26	4.6	24.6	4.59E+01
	6	30.2	5.92	4.75	28.7	5.35E+01
	7	30.2	5.86	4.9	25.4	1.10E+01
	8	29.8	5.73	4.95	26.5	6.24E+01
3rd survey						
	1	29.8	5.06	4.65	24.8	2.03E+01
	2	29.7	5.34	4.75	25.9	1.37E+01
	3	30.0	5.27	4.7	26.7	3.06E+01
	4	30.1	5.64	4.65	29.4	2.45E+01
	5	29.9	5.94	4.75	30.2	3.67E+01
	6	30.2	5.74	4.7	26.9	1.24E+01
	7	29.7	5.92	4.7	27.5	5.36E+01
	8	30.0	5.86	4.9	26.4	9.36E+01

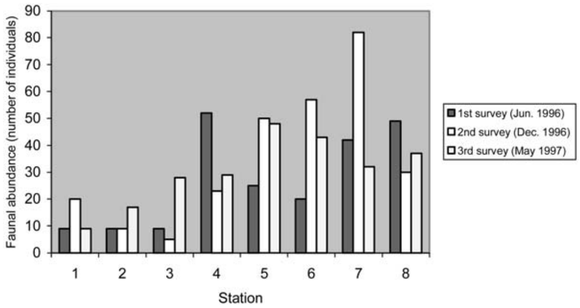


Figure 7. Total faunal abundance at eight stations of Pulau Semakau in the three surveys.

other stations during all three surveys. There were no significant differences in abundance among the three surveys (One-way ANOVA, $df = 2$, $F = 0.282$, $p = 0.757$).

Faunal biomass was affected by family composition, and was higher when there were more bivalves and crabs. As with abundance, stations 1, 2 and 3 had significantly less biomass than other stations further from the construction area (One-way ANOVA, $df = 6$, $F = 2.682$, $p = 0.0485$). No significant differences were observed across all stations for the three surveys (One-way ANOVA, $df = 2$, $F = 2.965$, $p = 0.0734$).

Significant differences in faunal diversity were observed among the eight stations (One-way ANOVA, $df = 6$, $F = 2.653$, $p = 0.0502$). Station 5 yielded the highest diversity followed by stations 3 and 8. No significant changes were observed for the eight

Table 2. Pearson correlation coefficients (r) and probability (p) among environmental parameters (sed-rate: sedimentation rate, 0/I: organic/inorganic ratio, sed: samples from seabed sediment, trap : samples from sediment traps, *: significant correlation)

		Depth	Sed-rate	Silt/clay (%)	O/I (sed)	O/I (trap)	NH_4^+ (sed)	NH_4^+ (trap)
Sed-rate	r	0.38187						
	p	0.0656*						
Silt/clay (%)	r	0.31257	0.68036					
	p	0.137	0.0003*					
O/I (sed)	r	0.00628	−0.26341	−0.40209				
	p	0.9768	0.2136	0.0514*				
O/I (trap)	r	0.13319	−0.31381	−0.32927	0.54951			
	p	0.535	0.1354	0.1161	0.0054*			
NH_4^+ (sed)	r	−0.28664	0.0144	0.13408	−0.4525	−0.01488		
	p	0.1745	0.9468	0.5322	0.0264*	0.945		
NH_4^+ (trap)	r	−0.15964	−0.04283	−0.22611	0.37047	0.39713	0.24438	
	p	0.4562	0.8425	0.288	0.0747*	0.0547*	0.298	
NH_4^+ (water)	r	0.20928	−0.41309	−0.44155	0.37679	0.32541	−0.42366	−0.01694
	p	0.3264	0.0448*	0.0308*	0.0695*	0.1207	0.0391*	0.9374

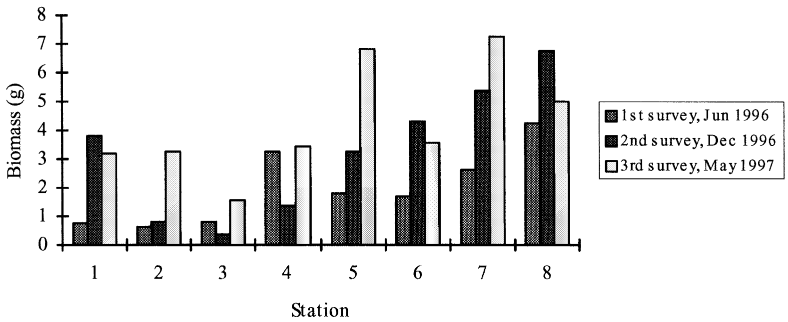


Figure 8. Total biomass at the eight stations around Pulau Semakau in the three surveys.

stations during the three surveys (One-way ANOVA, $df = 2$, $F = 0.781$, $p = 0.471$).

Polychaetes (Phylum Annelida) made up the majority of specimens collected from all stations (491 specimens or 66.8%) (Fig. 10). Crustaceans, including amphipods and isopods, were the next largest faunal group (192 specimens or 26.1%). At stations 2 and 3 during the second survey, only polychaetes were found. The total number of crustaceans increased with increasing distance from the construction area. Individuals from Phyla Mollusca and Echinodermata were only found in a few stations. Molluscs were mostly found in stations further away from the construction area (Stations 5, 6, 7 and 8).

Multidimensional Scaling (MDS)

The faunal data (non-standardized, double root-transformed) from eight stations were pooled for each station and plotted in two-dimensional MDS arrays for each survey. The resulting MDS arrays had stress values ranging from 0.01–0.07 (Fig. 11), indicating that the two-dimensional plots fitted the rank similarity matrices (Bray–Curtis) within acceptable range.

According to the results from ANOSIM (Table 3), stations 1, 2, 7 and 8 were significantly different from the other stations during the first survey (<5%). In the second survey, the MDS array using combined data suggests that stations 2, 3 and 4 differed from the rest. Stations 1, 2, 3 and 4 also differed significantly from the rest from the ANOSIM test (Table 4). In the MDS array for the third survey, stations 1 and 2, and sta-

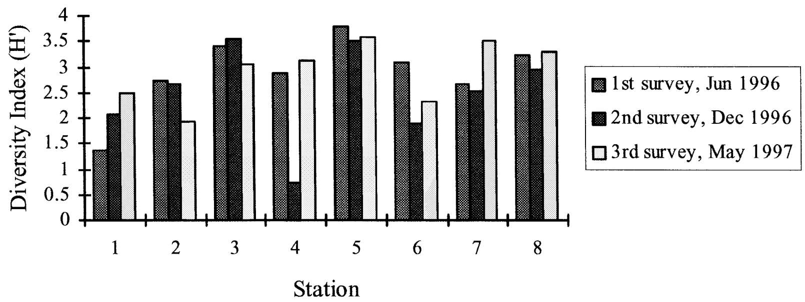


Figure 9. Shannon–Weaver diversity index of benthic communities at eight stations around Pulau Semakau in the three surveys.

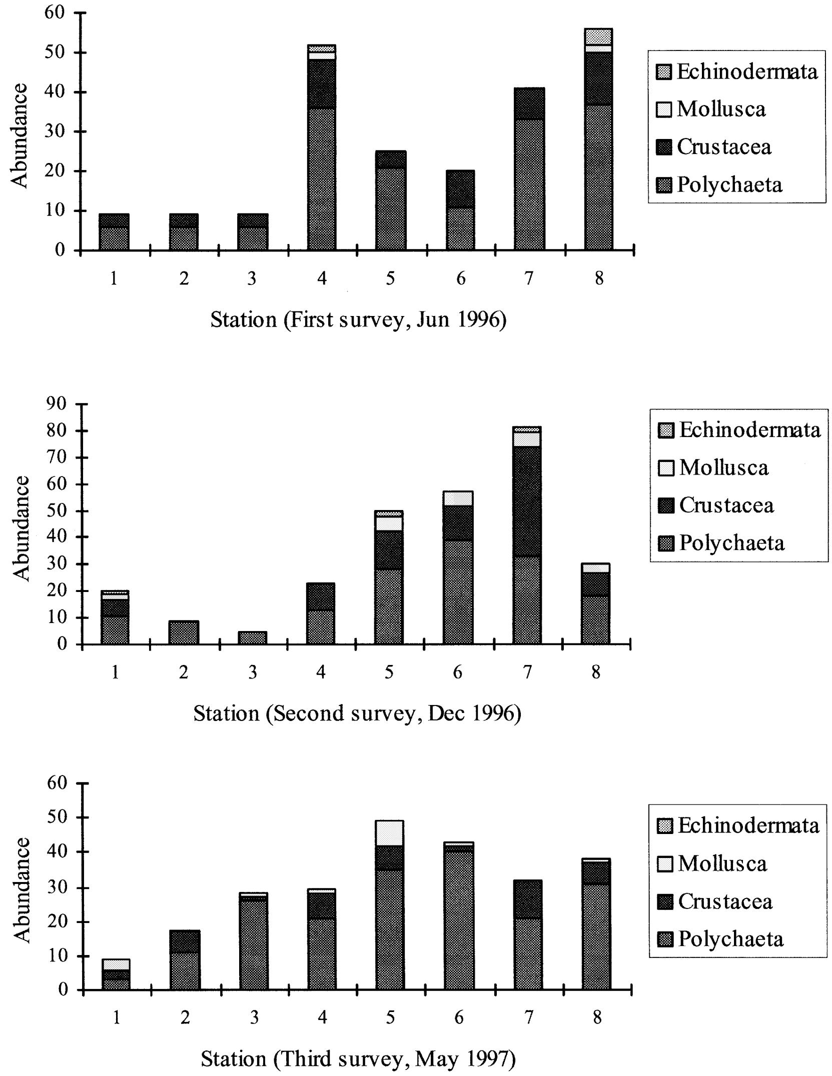
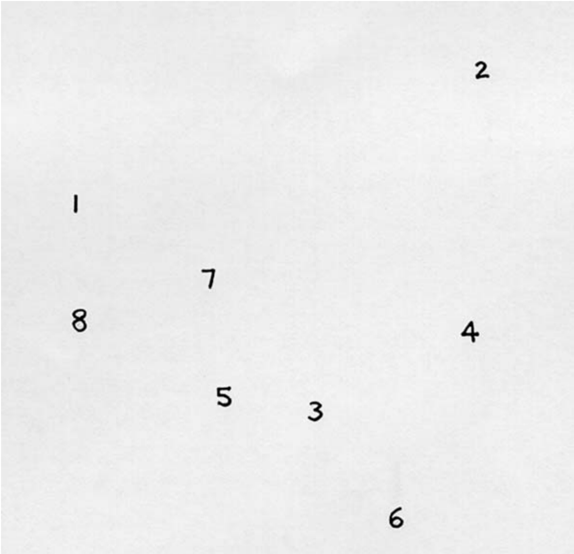


Figure 10. Distribution of taxa among the eight stations around Pulau Semakau in the three surveys.

tions 4 and 7 clustered away from the other stations. A similar result was observed using ANOSIM (Table 5).

Stations were also grouped using data from all three surveys to note differences between surveys (Fig. 12). Much of the change in faunal diversity



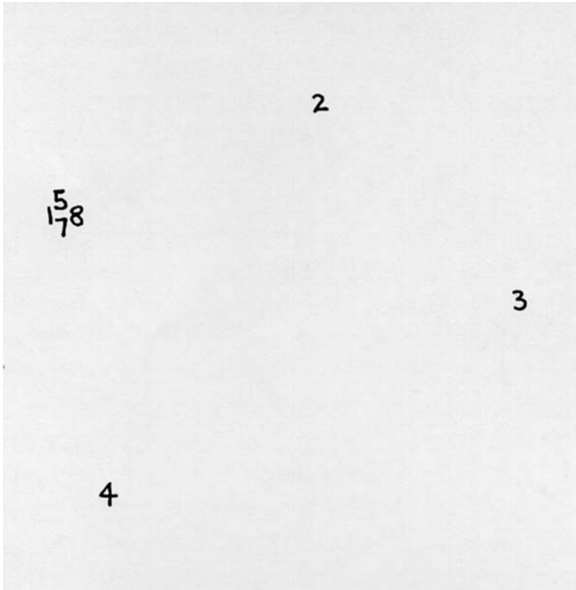


Figure 11. (a) Two-dimensional MDS configuration for double root-transformed benthic fauna data of eight stations around Pulau Semakau during the first survey, using sum data of replicates from each station (stress value = 0.07). Numbers indicate stations. (b) Two-dimensional MDS configuration for double root-transformed benthic fauna data of eight stations around Pulau Semakau during the second survey, using sum data of replicates from each station (stress value = 0.01). Numbers indicate stations (note that stations '6' and '8' are in the same position in the array). (c) Two-dimensional MDS configuration for double root-transformed benthic fauna data of eight stations around Pulau Semakau during the third survey, using sum data of replicates from each station (stress value = 0.01). Numbers indicate stations.

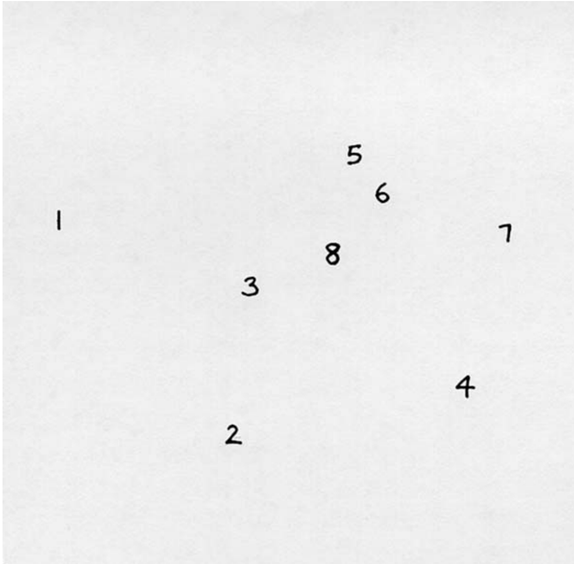


Figure 11. (Continued.)

Table 3. Summary of pairwise significance levels (%) of faunal communities between stations during the first survey by ANOSIM tests

Station	1	2	3	4	5	6	7
2	0.8						
3	1.6	8.7					
4	0.8	13.5	93.7				
5	0.8	1.6	37.3	23.8			
6	0.8	0.8	13.5	30.2	2.4		
7	3.2	3.2	15.9	6.3	13.5	0.8	
8	0.8	1.6	1.6	3.2	0.8	0.8	0.8

Table 4. Summary of pairwise significance levels (%) of faunal communities between stations during the second survey by ANOSIM tests

Station	1	2	3	4	5	6	7
2	10.3						
3	0.8	1.6					
4	0.8	0.8	1.6				
5	0.8	0.8	13.5	91.3			
6	0.8	0.8	4.8	38.1	71.4		
7	1.6	2.4	4.8	3.2	12.7	8.7	
8	0.8	0.8	0.8	91.3	21.4	31	1.6

between surveys occurred after survey 1, and stations further away from the construction area are also ob-

Table 5. Summary of pairwise significance levels (%) of faunal communities between stations during the third survey by ANOSIM tests

Station	1	2	3	4	5	6	7
2	4.8						
3	0.8	27					
4	4	16.7	56.3				
5	1.6	9.5	32.5	58.7			
6	0.8	6.3	23.8	13.5	78.6		
7	5.6	2.4	3.2	12.7	20.6	4	
8	0.8	6.3	24.6	50	15.9	1.6	0.8

served to exhibit less change in diversity compared to nearer stations.

Indicator families

Polychaete families such as Eunicidae, and Nephtyidae were present in almost all stations, and were most abundant during the three surveys. Families Spoinidae and Arenicolidae were also present in high proportions at the third survey. The dominant families contributing to the group similarity was ascertained (Table 6). Stations 1, 2 and 3, which were closest to the construction area were dominant in eunicids, amphipods and isopods during surveys 2 and 3. They were also grouped together (Group 1) in the MDS ordination (Fig. 12). In contrast, other stations, and stations during survey 1 (Groups 2 and 3) were dominant in Arenicolidae, Nephtyidae and Eunicidae. Group 1 had a lower abundance of Arenicolidae and Nephtyidae, and higher abundance of Eunicidae and Flabelligeridae than Group 2. Molluscs and Processidae (Phylum Crustacea) were present in Group 2 stations but not in Group 1. Amphipods and isopods, on the contrary, were abundant in Group 1 stations. Group 3 had higher abundances of Nephtyidae, Spoinidae, and the crustacean families Pilummidae and Processidea than stations in the other groups.

Relationship between environmental factors and benthic fauna

The correlation of sedimentation rate and fauna abundance, family number, diversity and biomass was analysed using the regression method (Table 7). There is good negative correlation between sedimentation rate and abundance ($p < 0.05$). According to Pearson correlation coefficients and probability, abundance decreased with increasing sedimentation rate. Diversity and biomass did not show significant correlation ($p > 0.05$) with respect to sedimentation rate. There was significant negative correlation between silt/clay percentage and family number and faunal abundance, which decreased markedly when the sediment became finer (family number $r = -0.606$, abundance $r = -0.647$). The changes in diversity and biomass were not as marked although they showed the same trend with respect to the silt/clay fraction in sediment. The

Table 6. Dominant families contributing to the similarity of each group (ref. Fig. 12), average abundances and percentage frequency during the three surveys

	Family	Mean no. of individuals	Frequency (%)
Group 1	Eunicidae	40	32.57
	Amphipod families	18.3	24.85
	Isopod familes	13.3	23.7
	Flabelligeridae	8.3	8.42
	Nereidae	15	6.06
	Glyceridae	3.3	2.48
	Others	–	1.92
Group 2	Arenicolidae	43.3	31.57
	Nephtyidae	25	21.84
	Eunicidae	23.3	12.83
	Apheidae	16.7	10.47
	Tellinidae	11.7	9.62
	Sternapsidae	25	4.54
	Cirratulidae	5	4.19
	Pilumnidae	18.3	2.32
	Terebellidae	3.3	1.32
	Others	–	1.3
Group 3	Eunicidae	50	12.28
	Nephtyidae	53.3	11.22
	Arenicolidae	46.7	10.86
	Amphipod familes	42.5	9.04
	Isopod families	15	8.52
	Spionidae	35	7.96
	Tellinidae	26.7	6.02
	Alpheidae	38.3	5.51
	Cirratulidae	15	4.11
	Pilumnidae	26.7	4.01
	Nereidae	12.5	3.56
	Terebellidae	6.7	3.29
	Glyceridae	10	2.46
	Capitellidae	22.5	2.32
	Syllidae	9.2	2.29
	Others	–	6.55

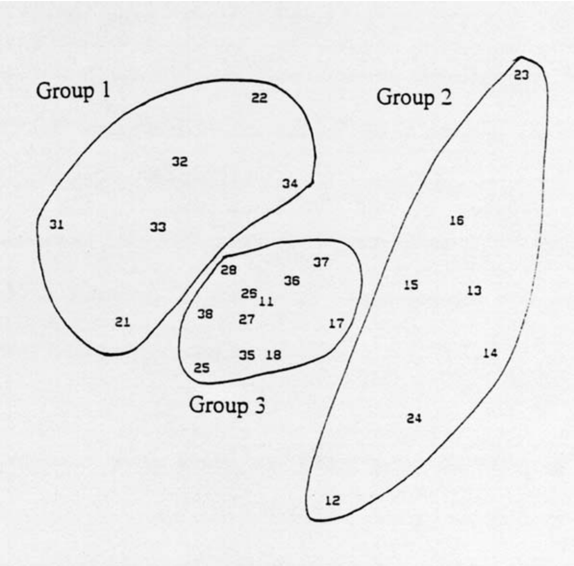


Figure 12. Two-dimensional MDS configurations for double root-transformed benthic fauna data of eight stations around Pulau Semakau during the three surveys using sum data of replicates from each station (stress value = 0.18). The first digit of each number = survey number, second digit = station number.

correlation is significantly negative between water ammonium concentration and faunal community, as well as with biomass.

Statistical analysis of environment parameters in relation to benthic communities

Principal component analysis (PCA) using environmental parameters produced a total of 8 principal components, 5 of which explained 90.4% of the total variance (Table 8). Environmental variables were assigned to one of the five vectors based on relative eigenvalues within and among vectors. Sedimentation rate, silt/clay fraction in sediment, organic and inorganic matter ratio comprised the majority of the first component (PC 1), indicating that sedimentation effect accounted for 36.7% of the total variance. The second component (PC 2), which explained 21.6% of the total variance, consisted of depth and ammonium concentration in bottom sediment. NH_4^+ concentration in trap sediment and organic matter in trap sediment comprised the major portion of PC 3, PC 4 and PC 5.

Discussion

Impact of sedimentation on marine environment

Sedimentation rates varied spatially at the eight stations, with the two stations nearest the rock bund construction having the highest rates, and further stations having lower rates. This indicated that the main source of the increase in sedimentation was due to construction activity at the rock bund. Patch reefs occurred between some stations and the construction area and altered water current direction, which prevented sediment spreading to some extent. These stations yielded low sedimentation rates although they were close to the construction area.

Statistical analysis showed that there were no significant changes in environmental parameters during three surveys except for increased sedimentation rates. An activity with a significant input was the drain constructed at the eastern part of Pulau Semakau near station 4. However, the impact from this input was localised and only increased the sedimentation rates of nearby stations.

The construction material included marine and inland clay, silt, rock and sand (Nathan, 1993). Sediment screens were used to contain the spread of sediment but this did not exclude fine particles from entering the surrounding waters. It was clearly shown from the analysis that the input of fine sediment particles changed the seabed sediment composition.

There was an inverse relationship between sedimentation rate and other sediment-related parameters such as organic/inorganic matter ratio, and ammonium concentration in sediment. These parameters were evidently influenced by the increased sedimentation from the construction activities. The construction materials are nutrient-poor, and contain little organic matter (Chua & Lee, 1984), and there was less organic matter input at the stations near the construction area.

The large amount of poor nutrient input also altered the nutrient cycle in these stations as limited nutrients may decrease biological productivity. According to Nedwell & Trimmer (1996), more than 90% of the flux of nitrogen through the sediment was lost as gases, and 50% of the nitrogen ammonification of organic matter was converted to gases by coupled nitrification-denitrification within the sediment. In this study, the bottom ammonium concentration and organic matter were lowered with the sediment input, and nitrogen may be lost as a result. Benthic fauna also consumed some nitrogen resulting in large biomass in

Table 7. The result of Pearson correlation coefficients (r) and probability (p) between environmental parameters and faunal communities (sed-rate: sedimentation rate, 0/1: organic/inorganic ratio, sed: samples from seabed, trap: samples from sediment trap, *: significant correlation)

		Family number	Abundance	Diversity	Biomass
Sed-rate	r	−0.3925	−0.60129	−0.29659	−0.18811
	p	0.0578	0.0019*	0.1593	0.3787
Silt/clay (%)	r	−0.60644	−0.64748	−0.35724	−0.35225
	p	0.0017*	0.0006*	0.0866	0.0914
O/I (sed)	r	0.18308	0.33524	0.12332	0.32505
	p	0.3918	0.1093	0.5659	0.1212
O/I (trap)	r	0.18921	0.27163	0.15532	0.34255
	p	0.3759	0.1992	0.4686	0.1013
NH_4^+ (sed)	r	−0.24571	−0.21718	−0.05124	−0.3958
	p	0.2471	0.308	0.812	0.0556
NH_4^+ (trap)	r	0.24278	0.20828	−0.10366	0.18237
	p	0.253	0.3287	0.6298	0.3937
NH_4^+ (water)	r	0.64988	0.76913	0.25303	0.65927
	p	0.0006*	0.0001*	0.2329	0.005*

Table 8. Eigenvectors for the first five principal components (PCA) from nonstandardized and 4th root-transformed environmental parameters. (sed-rate: sedimentation rate, O/I: organic/inorganic ratio, sed: samples from seabed, trap: samples from sediment trap)

Parameters	PC1(36.7%)	PC2(58.3%)	PC3(74.4%)	PC4(84.0%)	PC5(90.4%)
Depth	−0.064	0.611	−0.221	−0.508	−0.009
Sed-rate	−0.402	0.296	−0.389	0.201	−0.172
Silt/clay (%)	−0.462	0.233	−0.221	0.043	−0.091
O/I (sed)	0.45	0.159	−0.287	0.426	0.155
O/I (trap)	0.425	0.06	−0.359	−0.318	0.562
NH_4^+ (sed)	−0.211	−0.542	−0.203	−0.56	0.006
NH_4^+ (trap)	0.206	−0.279	−0.656	0.074	−0.534
NH_4^+ (water)	0.388	0.29	0.261	−0.313	−0.58

the stations with high nutrient input but little bottom sediment nutrient. The inverse correlation between NH_4^+ concentration in water and bottom sediment suggested that the water carried away most of this soluble nutrient, leaving a small amount in the bottom sediment.

Aside from sedimentation, the other *in situ* parameters were not affected by the construction activity. Over the study period, these parameters did not differ significantly over time and thus did not affect the benthic community significantly.

Impact of sedimentation on benthic communities

The main adverse biological effects were likely to be connected to the rate of sedimentation rather than the chemical composition of the sediment itself. Sedimentation greatly affected faunal communities not only physically but also through changing sediment composition, organic matter and nutrient input. This study showed a strong correlation between changes in the benthic community and the amount of clay/silt fraction in the sediment. Nicolaidou et al. (1989) found that changes in the particle size composition of the sediment and an increase in the instability of the environment affected benthic organisms most directly. Agard et al. (1993) also concluded that sediment type is the major overall determinant of community composition. Maxon et al. (1997) thought that sediment grain size alone was the best predictor of amphipod mortality. Accordingly, this study indicated that changes in faunal communities are mainly influenced by sediment composition.

The change in nutrient concentration in the water and sediment resulting from increased sedimentation also impacted the benthic community. In the benthos, the limiting nutrient for the faunal community is ammonium, while phosphate concentration has no essential effect (Banta et al., 1995). Studies on the impact of high organic pollution on benthic fauna (Heip, 1992; Kroncke et al., 1992) found that faunal abundance decreased in highly polluted areas. In this study, limited organic matter and NH_4^+ concentration in the sediment input to the seabed correlated with decreasing faunal abundance and family numbers.

Distinct changes in community composition was observed at stations close to the construction area, with a marked reduction in family numbers, a decrease in abundance and changes in dominance patterns. A faunal composition representative of a disturbed zone (e.g., Group 1) was found at stations near the construction area, while the stations further away had a more homogenuous fauna composition indicating no heavy sedimentation in these areas. Similar faunal changes along an environmental parameter gradient have been described from a number of studies (Littlepage et al., 1984; Nicolaidou et al., 1989; Probert, 1981; Rygg, 1985). They indicated that the main pattern of changes in faunal composition along gradients of disturbance is largely independent of the type of factors inducing the disturbance.

Principal Component Analysis (PCA) showed that the principle factors contributing to changes in faunal communities are sediment grain size, sedimentation rate and nutrient level in the bottom sediment. Benthic organisms are smothered and killed wherever there is a rapid, heavy settling of sediment. It is believed that heavy sedimentation mainly has a physical effect on the benthic animals, either directly killing them or making the environment so unstable that few species are able to survive. In the construction area, a sedimentation rate in the order of 0.085 g cm^{-2} d^{-1} clearly had an adverse effect on fauna while a sedimentation rate of 0.02 g cm^{-2} d^{-1} did not result in observable biological effects. Studies of macrofauna in the disposal area of red clay concluded that the communities appeared normal and undisturbed when exposed to sedimentation in the order of a few mm to cm (Bottom, 1979). Nichols et al. (1978) found that most species common in soft-bottom communities could avoid burial with 5–10 cm of sediment. Turk & Risk (1981) investigated effects of sedimentation on three species of infauna, and found that degree of impact was species dependent and varied with rates, depths and grain size of sediment deposition.

Persistent instability of bottom sediments is stressful and reduces faunal diversity (Probert, 1981; Aller & Dodge, 1974). In addition, sedimentation of the construction material gradually makes the bottom sediments more homogeneous and reduces pore space, which would restrict niche availability and hence lead to low faunal diversity (Gray et al., 1990; Ward, 1975). The faunal communities and sedimentation rates in the three surveys had no significant changes except for stations 4 and 5 which were nearest to the new storm drain built after the first survey. This suggested that the communities at other stations were approaching the homogeneous state after prolonged exposure to the same degree of stress.

The indicator families

The multivariate methods applied in this study show three faunal groups among the survey stations. Principal families contributing to these groups were different and dependent on tolerance to different sedimentation rates and nutrient levels. Families more abundant in heavy sedimented stations had high tolerance for fine sediment and low nutrient levels while families absent from these stations were non-tolerant to these impacts. The SIMPER method successfully categorises the tolerant and non-tolerant families, and the findings support results from Gray et al. (1990) that the major differences in faunal composition from polluted to non-polluted sites are firstly due to changes in abundance patterns, and secondly to changes in presence-absence of families.

If individuals are killed by smothering, opportunistic species will dominate, and if the effect of the perturbation is persistent the opportunistic species can be expected to dominate continuously (Mirza & Gray, 1981). In Olsgard & Hasle's (1993) study, sites clearly impacted by smothering of tailings all have small, opportunistic polychaetes as the predominant fauna. In this study the predominant fauna at the impacted stations were the polychaete families Eunicidae, Flabeligeridae, Nereidae and Glyceridae, which all have small and opportunistic species. In less impacted stations, more crustaceans and molluscs were present.

The degree of disturbance depends on sedimentation rates as well as the species composition of the already established bottom communities. In Olsgard and Hasle's (1993) study, there was a conspicuous lack of larger tubicolous polychaetes at the most heavily sediment-impacted sites.

Conclusion

The construction activity affected the surrounding marine area by increasing the sedimentation rate, altering the sediment composition, and decreasing the nutrient input along a spatial gradient. Increased sedimentation ultimately impact on the nearby benthic communities by decreasing faunal abundance, family numbers and diversity.

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