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A STUDY ON POSSIBLE SHORT-TERM ENVIRONMENTAL EFFECTS OF WBM CUTTING DISCHARGES IN THE FRISIAN FRONT AREA (NORTH SEA)

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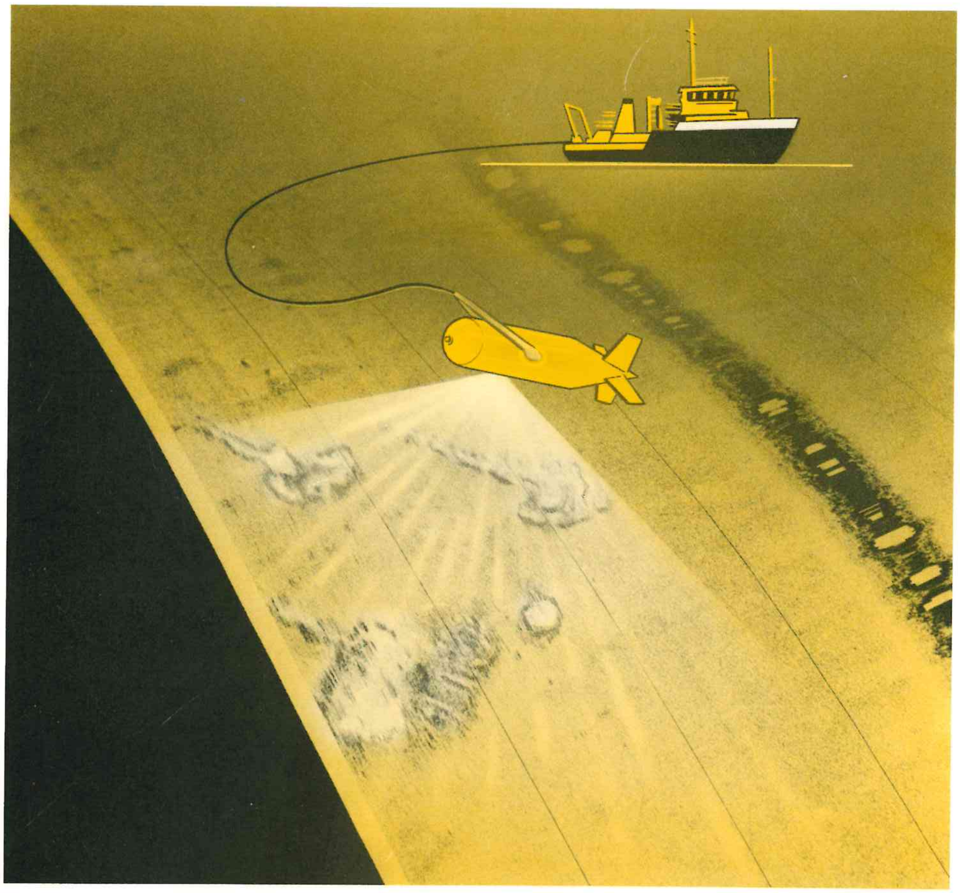

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Mobil Producing Netherlands Inc.,
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SUMMARY AND CONCLUSIONS

The use of oil based muds (OBM) in drilling operations in the North Sea has recently been subjected to stringent requirements. In parts of the Dutch sector discharges of drill cuttings contaminated with OBM were prohibited by April1992 and a complete prohibition of OBM cutting discharges has taken effect from January 1993. Anticipating the new regulations, some oil companies refrained from further OBM discharges already in 1991 and decided to use preferably water based muds (WBM) but, when the need for the use of OBM is urgent, to bring oil contaminated cuttings to land.

In the summer of 1991 two exploration wells were drilled in the Frisian Front area, using only WBM: at location L3-3 all drilled material was dumped on the seabed, at location L6-3 only the material from the top hole. In the latter case the material from the deeper sections was brought to land. After drilling was completed the rigs were removed from both locations. In order to assess whether dumping on the seabed of WBM contaminated material generated adverse effects on the benthic community, combined biological and chemical surveys were carried out in October 1991 at both locations. This report presents the results of both surveys and gives some recommendations for future research.

According to a table listing the amounts and composition of the materials dumped at L3-3 (provided by the oil company concerned), barite was a substantial constituent of the muds used at this location. Hence, as could be expected, chemical analyses of the sediment revealed a clear gradient in Ba concentrations, showing high levels within 100 m from the discharge site, which gradually decreased to approximately background level at 1000 m. A check on the absence of oil in the sediment by means of GCMS analysis of a sediment sample collected at the discharge site confirmed the absence of oil. Except for the discharge site itself, where the sediment was buried under a pile of cuttings in which hardly signs of animal life were observed, biological effects were not found, even not at a station as close as 25 m to the discharge site. The only slight indication of some disturbance in the vicinity of the drill site was the presence of a few specimens of the opportunistic species *Capitella capitata* at distances of 25 and 75 m.

At L6-3 a more complicated situation was met. Although the specification of drilling chemicals, provided by the company concerned, did not include barite, substantially elevated Ba concentrations were assessed in the sediment as far out as 500 m from the location. The origin could not be clarified, but the spatial pattern in concentration levels suggests that bariferous material has found its way to the seabed at or close to the drilling site. Moreover, traces of base oil were found close to the discharge site. In this case, the origin of the oil could be explained afterwards, since it appeared that contaminated service pipes had been used at L6-3. Previously the rig had been used for an OBM drilling at another location in the Dutch sector. Biological effects, in terms of an impoverished macrofauna community, could be clearly identified at 25 m and to a lesser extent at 75 m from the discharge site. At both stations, and at 125 m too, a slight indication of environmental stress was also seen by the presence of a few specimens of *Capitella capitata*. Since there were different sources of pollution at L6-3, it is not possible to specifically attribute the observed effects to either the known WBM cutting discharges or the additional contaminants.

The results and conclusions of the WBM studies at L3-3 and L6-3 may be summarized as follows:

1. L3-3: In terms of elevated Ba concentrations in the sediment, the spread of discharged material was detectable up to 500-1000 m from the discharge site.
2. L3-3: A sediment sample taken at the discharge site did not show any indication of elevated oil concentrations in the sediment.
3. L3-3: In the area investigated, including 14 stations from 25 up to 5000 m from the discharge site, adverse effects on the benthic community were not observed. This indicates that, at the short term, dumping of WBM with a chemical composition like the one used at L3-3 does not affect the benthic community.
4. L3-3: The only slight indication of organic pollution of the sediment was the presence of a few specimens of *Capitella capitata* within 75 m from the discharge site.
5. L3-3: The period elapsed between termination of the discharges and the biological survey may have been too short (2 months) to detect subtle biological effects.
6. L6-3: Biological effects were identified at both (of 2) sampling stations within 100 m from the discharge site. The effects at 25 m were obviously more severe than at 75 m.
7. L6-3: The biological effects at 25 m (a substantial reduction of the total macrofauna abundance and of most of the individual species) can only partly be explained by burying and subsequent suffocation of the fauna. At 75 m burying can not have been a significant mortality factor.
8. L6-3: The presence of a few specimens of *Capitella capitata* at 25, 75 and 125 m gave a subtle indication of organic pollution around the drill site.
9. L6-3: In the area between 125 m and 5000 m from the discharge site (residual current direction) no significant biological effects were observed.
10. L6-3: The chemical sediment analyses showed unexpectedly high Ba concentrations at most stations up to 500 m from the discharge site. GCMS-

analysis of a sample collected at the discharge site revealed a slight, but compared to background level (<7 mg·kg^{-1} dry weight) significantly elevated concentration (12.6 mg·kg^{-1} dry weight) of base oil in the sediment.

11. L6-3: The composition of the WBM used at L6-3 was different from that used at L3-3, which might explain the difference in the response of the macrofauna to the dumpings. However, it is not possible to decide that the biological effects observed at L6-3 should be attributed to the known WBM cutting discharges because of the presence of additional contaminants in the sediment around this location.
12. L3-3 and L6-3: The results suggest that, if there is any biological impact of WBM cutting discharges at all, the spatial extent of this impact at the short term does not exceed a radius of ≈100 m and is, therefore, small compared to affected areas around drill sites where OBM cuttings were dumped. At OBM locations gross biological effects usually occur up to a few hundreds of meters and subtle effects may be traced as far out as a few kilometres.
13. Further investigations are recommended for location L3-3, to verify the absence of adverse effects at the longer term. This location should be preferred over L6-3, because of the absence of additional pollutants. Location L6-3 is not appropriate to evaluate possible effects of WBM cutting discharges.
14. A follow-up survey at L3-3 should be based on the same small scaled sampling grid as used in the present study, because of the limited spatial extent of effects to be expected.

SAMENVATTING EN CONCLUSIES

De regelgeving met betrekking tot het gebruik van boorspoeling op oliebasis (oil based muds = OBM) bij booraktiviteiten op de Noordzee is sinds kort belangrijk aangescherpt. In delen van de Nederlandse sector is het lozen van OBM-houdend boorgruis met ingang van april1992 niet meer toegestaan en een volledig verbod op deze lozingen is vanaf januari 1993 van kracht. Vooruitlopend op de nieuwe maatregelen hebben sommige oliemaatschappijen in 1991 al besloten OBM-houdend boorgruis niet meer in zee te lozen en bij voorkeur boorspoelingen op waterbasis (water based muds = WBM) te gebruiken, of, wanneer aan het gebruik van OBM niet te ontkomen valt, het met olie verontreinigde boorgruis aan land te brengen.

In de zomer van 1991 werden in het Friese Front gebied 2 exploratieboringen verricht waarbij uitsluitend WBM werd toegepast: op lokatie L3-3 werd al het opgeboorde materiaal inclusief de boorspoeling op de zeebodem geloosd, terwijl op lokatie L6-3 alleen het WBM-gruis uit de bovenste sectie van het boorgat ter plaatse werd geloosd. Van deze laatste lokatie werd het gruis uit de diepere secties, die geboord werden met WBM van een andere samenstelling dan die welke in de bovenste sectie was gebruikt, naar land afgevoerd. Nadat het boren was beëindigd werden van beide lokaties de platforms verwijderd. Teneinde vast te stellen of lozing van WBM-houdend materiaal negatieve effekten heeft op de levensgemeenschap in de zeebodem, werd in oktober 1991 op beide lokaties een gecombineerd biologisch en chemisch veldonderzoek uitgevoerd. In dit rapport worden de resultaten van dit projekt gepresenteerd en enige aanbevelingen gedaan voor verder onderzoek.

De gegevens over hoeveelheid en samenstelling van het materiaal dat geloosd is op L3-3, volgens een tabel aangeleverd door de betreffende oliemaatschappij, laten zien dat bariet een substantieel bestanddeel vormde van de spoeling die op deze lokatie gebruikt werd. Zoals verwacht mocht worden lieten de chemische analyses dan ook een duidelijke gradient zien in barium-concentraties in het sediment: deze concentraties waren met name hoog binnen 100 m van het lozingspunt, namen met toenemende afstand geleidelijk af en bereikten op 1000 m ongeveer het niveau van natuurlijke achtergrondwaarden. Een controle op de afwezigheid van olie in het sediment aan de hand van een GCMS-analyse van een sediment-monster genomen op het lozingspunt bevestigde de afwezigheid van olie. Behalve op het lozingspunt zelf, waar het sediment was bedolven onder een hoop boorgruis waarin nauwelijks tekenen van leven waren te bespeuren, werden geen biologische effekten waargenomen, zelfs niet op het zeer nabij gelegen 25-m station. De enige vage aanwijzing dat er in de buurt van het lozingspunt sprake was van een zekere mate van verstoring werd gevonden in de aanwezigheid van enkele exemplaren van de opportunistische soort *Capitella capitata* op 25 en 75 m.

Op L6-3 werd een meer gecompliceerde situatie aangetroffen. Hoewel de specificatie van gebruikte chemicaliën, zoals aangeleverd door de betreffende oliemaatschappij, aangaf dat de geloosde boorspoeling geen bariet bevatte, werden aanmerkelijk verhoogde Ba-concentraties in het sediment vastgesteld tot op 500 m van de lokatie. De herkomst hiervan kon niet worden achterhaald, maar het ruimtelijke patroon in concentratie-niveau's doet vermoeden dat bariumhoudend materiaal op of dichtbij de boorlokatie op de zeebodem terecht is gekomen. Verder werden dicht bij het lozingspunt ook geringe concentraties olie in het sediment aangetroffen, die kon worden geïdentificeerd als olie die als basismedium in OBM wordt gebruikt. In dit geval kwam hiervoor achteraf een verklaring, toen bleek dat het systeem van leidingen op het platform, dat de boring op L6-3 heeft uitgevoerd, nog verontreinigd moet zijn geweest met restanten olie van een OBM-boring, die met dit platform tevoren op een andere lokatie in de Nederlandse sector was uitgevoerd. Biologische effekten, in de zin van een verarmde macrofaunagemeenschap, konden duidelijk worden aangetoond op 25 m en in minder sterke mate op 75 m van het lozingspunt. Op deze beide stations, maar ook op 125 m, gaf bovendien de aanwezigheid van enkele exemplaren van *Capitella capitata* een subtiele aanwijzing voor 'environmental stress'. Aangezien er op L6-3 sprake is van meer dan één vorm van verontreiniging, is het niet mogelijk de waargenomen effekten eenduidig toe te schrijven aan ófwel de bekende WBM-boorgruis lozingen ófwel de onvoorziene verontreiniging die daarnaast werd aangetroffen.

De resultaten en conclusies van het WBM-onderzoek op L3-3 en L6-3 kunnen als volgt worden samengevat:

1. L3-3: Aan de hand van de aangetroffen verhoogde Ba-concentraties in het sediment kon verspreiding van geloosd materiaal worden vastgesteld tot 500 à 1000 m van het lozingspunt.
2. L3-3: In een sediment-monster genomen op het lozingspunt werd geen verhoogde olieconcentratie aangetroffen.
3. L3-3: In het onderzochte gebied, dat 14 stations omvatte op afstanden varierend van 25 m tot 5000 m van het lozingspunt, werden geen negatieve effekten op de bodemfauna waargenomen. Dit wijst er op dat dumping van WBM, met een samenstelling zoals die welke op deze lokatie werd gebruikt, op de korte termijn geen schadelijke gevolgen heeft voor de bodemfauna.
4. L3-3: Alleen de aanwezigheid van enkele exemplaren van *Capitella capitata* binnen 75 m van het lozingspunt vormde een vage aanwijzing voor

een vorm van organische verontreiniging van het sediment.

5. L3-3: De periode die verstreken is tussen het einde van de lozingen en het biologische veldonderzoek (2 maanden) was wellicht te kort om eventuele subtiele effekten te kunnen aantonen.
6. L6-3: Biologische effekten werden aangetoond op beide stations die binnen 100 m van het lozingspunt werden bemonsterd. Op 25 m waren de effekten duidelijk meer uitgesproken dan op 75 m.
7. L6-3: De biologische effekten op 25 m (een aanmerkelijke afname in de totale fauna-dichtheid en in die van de meeste afzonderlijke soorten) kunnen slechts ten dele worden verklaard door bedelving en bij gevolg verstikking van de fauna. Op 75 m kan bedelving in het geheel geen factor van betekenis zijn geweest.
8. L6-3: De aanwezigheid van enkele exemplaren van *Capitella capitata* op 25, 75 en 125 m bood een subtiele aanwijzing voor organische verontreiniging rond de boorlokatie.
9. L6-3: In het gebied tussen 125 en 5000 m van het lozingspunt (reststroomrichting) konden geen significante effekten worden aangetoond.
10. L6-3: Uit de chemische sediment-analyses kwamen onverwacht hoge Ba-concentraties naar voren op de meeste stations tot op 500 m van het lozingspunt. Uit de GCMS-analyse van een monster genomen op het lozingspunt bleek dat het sediment verontreinigd was met een geringe - maar, in vergelijking tot achtergrondniveau ($<7 mg \cdot kg^{-1}$ droog sediment), significant verhoogde - concentratie OBM-olie ($12.6 mg \cdot kg^{-1}$ droog sediment).
11. L6-3: De samenstelling van de WBM die op L6-3 is gebruikt was anders dan die op L3-3, hetgeen als verklaring aangevoerd zou kunnen worden voor het verschil tussen beide lokaties wat betreft de respons van de macrofauna op de lozingen. Men mag echter niet concluderen dat de biologische effekten op L6-3 het gevolg zijn van de bekende WBM-lozingen, vanwege de aanwezigheid van andere verontreiniging in het sediment aldaar.
12. L3-3 en L6-3: De resultaten wijzen er op dat, als er al enig biologisch effekt van de WBM-lozingen uitgaat, de reikwijdte van dit effekt op de korte termijn beperkt blijft tot een gebied binnen een straal van ≈100 m rond het lozingspunt. Een dergelijke ruimtelijke omvang is klein in vergelijking tot lokaties waar OBM-gruis is geloosd en waar belangrijke effekten zich doorgaans voordoen tot op enige honderden meters afstand en subtiele effekten kunnen worden gedetecteerd tot op enkele kilometers.
13. Aanbevolen wordt om vervolgonderzoek uit te voeren rond L3-3, teneinde te verifiëren of op de langere termijn geen effekten optreden. Aan deze lokatie dient de voorkeur te worden gegeven, omdat hier geen additionele bronnen van verontreiniging werden aangetroffen. Lokatie L6-3 is niet geschikt om eventuele effekten van WBM-boorgruislozingen nader te onderzoeken.
14. Een vervolgonderzoek bij L3-3 dient uitgevoerd te worden aan de hand van een ruimtelijk even kleinschalig netwerk van monsterstations als gehanteerd is in de voorliggende studie, in verband met de beperkte schaal waarop naar verwachting effekten zich mogelijk zullen voordoen.

1 INTRODUCTION

1.1 GENERAL PART

Offshore drilling activities entail discharges of large amounts of drill cuttings on the seabed. The material dumped is always contaminated with residuals of drilling muds. Because the muds utilized in the drilling process have several different functions (*e.g.* cooling and lubricating of the drill bit, transport of cuttings to the surface, sealing the wall of the hole in porous formations), their composition is generally complex. In the 70's the base fluid of the muds was generally water (WBM = water based muds), with additions like barite, bentonite, inorganic salts, polymers, surfactants and other substances. In the 80's oil based muds (OBM) came into use, which enhanced the drilling efficiency, enabled deviated drilling and prevented deep salt formations from going into solution. When brought to the surface, the OBM cuttings are shaked on sieves to regain the drilling fluid, but the material dumped still contains residuals of adhering drilling muds, even when additional washing procedures are applied. In preceding years attention has been paid particularly to the discharges of OBM cuttings with respect to their environmental impact, and research in different sectors of the North Sea generally focussed on these oil contaminated drill cuttings. Broadly speaking, the outcome of these studies was that dumping of OBM cuttings involves high disturbance of the benthic fauna composition up to some hundreds of meters from well sites and that subtle effects can be detected up to 2 or even ≈10 km (*e.g.* MULDER *et al.*, 1987, 1988; REIERSEN *et al.*, 1989; GRAY *et al.*, 1990; DAAN *et al.*, 1990, 1991, 1992; KINGSTON, 1992; BAKKE *et al.*, 1991). The insight obtained in the spatial and temporal extent of environmental stress in the benthic ecosystem caused by these discharges has recently led to tightened legislation with respect to concessions. In parts of the Dutch sector, the so-called Environmental Zone (ZEVENBOOM *et al.*, 1992a), dumping of oil contaminated cuttings was prohibited from April 1992 (ANONYMOUS, 1992), but some oil companies already voluntarily refrained from further discharges of OBM cuttings and decided to bring the material to land. A complete prohibition of OBM cutting discharges in the Dutch sector has taken effect from January 1993.

With the introduction of the new regulations, further investigations on the (short-term) impact of OBM related dumpings have become less relevant and, as a consequence, the attention has shifted to WBM related dumpings. The question arose whether these discharges can lead to environmental stress, and to what extent they affect the benthic fauna composition or the abundance of individual species. An important question in particular is whether disturbance stretches beyond the small area around the very discharge site, where several species are expected to die from suffocation, merely due to the fact that they are buried under a layer of cuttings.

In 1991 the oil companies drilling in the Frisian Front have initiated a research programme to investigate the possible short-term effects of WBM cutting discharges at 2 drilling sites in the Frisian Front area (Fig. 1). Both locations were drilled in August 1991 and only WBM cuttings were discharged. At location L3-3 the complete hole was drilled using WBM and all material was discharged. At L6-3 only the material from the top hole was dumped on the seabed. Material from the deeper sections, also drilled with WBM but with a different composition than used for the top hole, was brought to land. At both locations discharge of WBM cuttings took place through a chute which extended to a depth of about 5 meters above the seabed, in order not to disturb algal blooms. Composition and amounts of drilling chemicals in the material dumped are listed in Table 1, showing that barite, which can serve as a fine tracer for the spread of

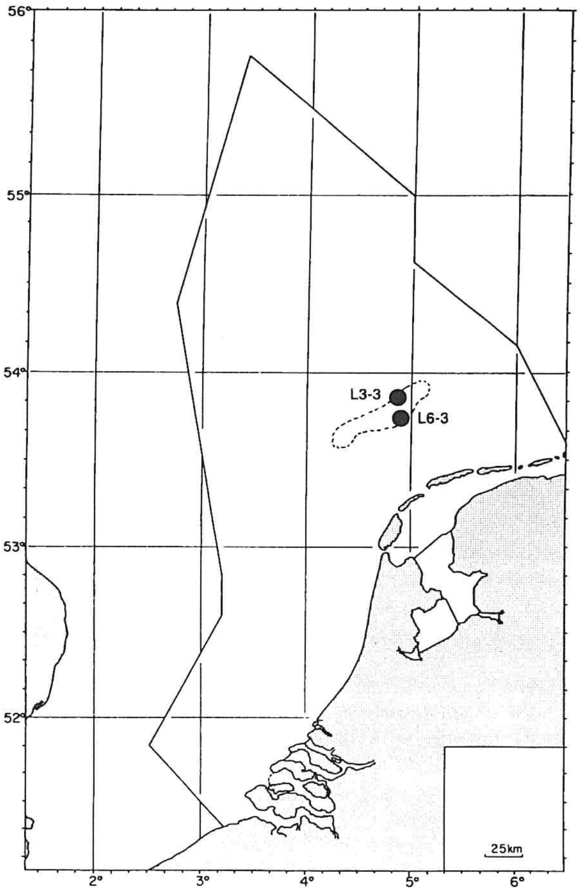

Fig. 1. Positions of drilling sites L3-3 and L6-3 in the Dutch sector of the North Sea. Broken line: boundary of the Frisian Front according to GEE *et al.* (1991).

TABLE 1
Amounts and composition of mud and cuttings discharged at L3-3 and L6-3 (only top hole discharged).

	L3-3	*L6-3*
drilled material (sand and clay cuttings)	?	±345 m^3
idem - dry weight (tonnes)	?	±930 t
WBM	1607 m^3	1933 m^3
idem - dry weight (tonnes)	749 t	58 t
barite (Bariumsulphate)	470 t	-
bentonite (clay)	88 t	35 t
starch (carboxymethyl cellulose)	18 t	18 t
caustic soda (NaOH)	4 t	3 t
Salt (NaCl)	163 t	-
Ferro-lignosulphonate (chrome-free)	0.525 t	0.77 t
Polysaccharid	1.5 t	0.11 t
Polyanionic cellulosic polymer	3.3 t	-
detergent	0.168 t	-
Acrylamide/Na-acrylate copolymer	0.145 t	-
Anionic surfactants (isopropyl alcohol)	0.042 t	-
Ammonium bisulphite solution	0.116 t	-
wood shavings and such	0.5 t	-
bicarbonate	-	0.78 t

dumped cuttings, was only discharged at L3-3.

Field surveys around both locations took place in October 1991, ≈2 months after completion of drilling, and included macrofauna sampling at 14 stations around each location. Sediment subsamples were taken for barium analyses, and at the discharge sites an additional sample was taken for GCMS analysis to verify the absence of oil contamination. Since it was expected that the spatial extent of disturbance around these WBM locations would be smaller than at OBM discharge sites, a grit of sampling stations was chosen concentrated more closely to the discharge sites than in routine OBM surveys. The occurrence of biological effects was detected by studying possible gradual changes in fauna composition and spatial abundance patterns of individual species that could be related to distance to the location. It was anticipated that effects of smothering could be expected to occur only at the station closest to the discharge site, *i.e.* at 25 m. At 75 m such a smothering effect was considered *a priori* negligible. This report presents the results and conclusions of both WBM surveys and gives some recommendations with respect to future research.

1.2 ACKNOWLEDGEMENTS

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2 METHODS

2.1 POSITIONING AND SAMPLING

The locations L3-3 and L6-3 are both abandoned. After the drilling of the wells was completed, the rigs were removed. Hence the positions had to be traced by accurate positioning techniques.

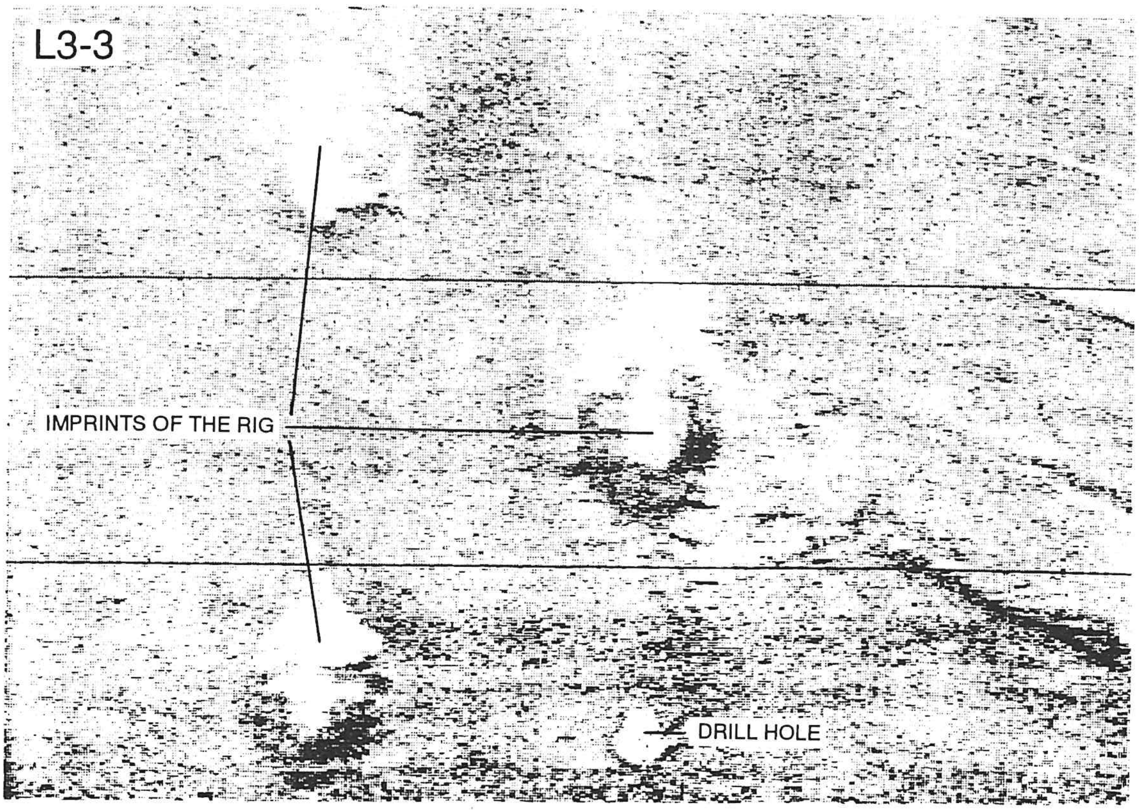
The field surveys were carried out on board of the R.V. Mitra in the 2nd and 3rd week of October. Accurate positioning was performed by using DGPS. Side-scan sonar records, showing the imprints of the rig (Fig. 2), confirmed that the ship was at the right position.

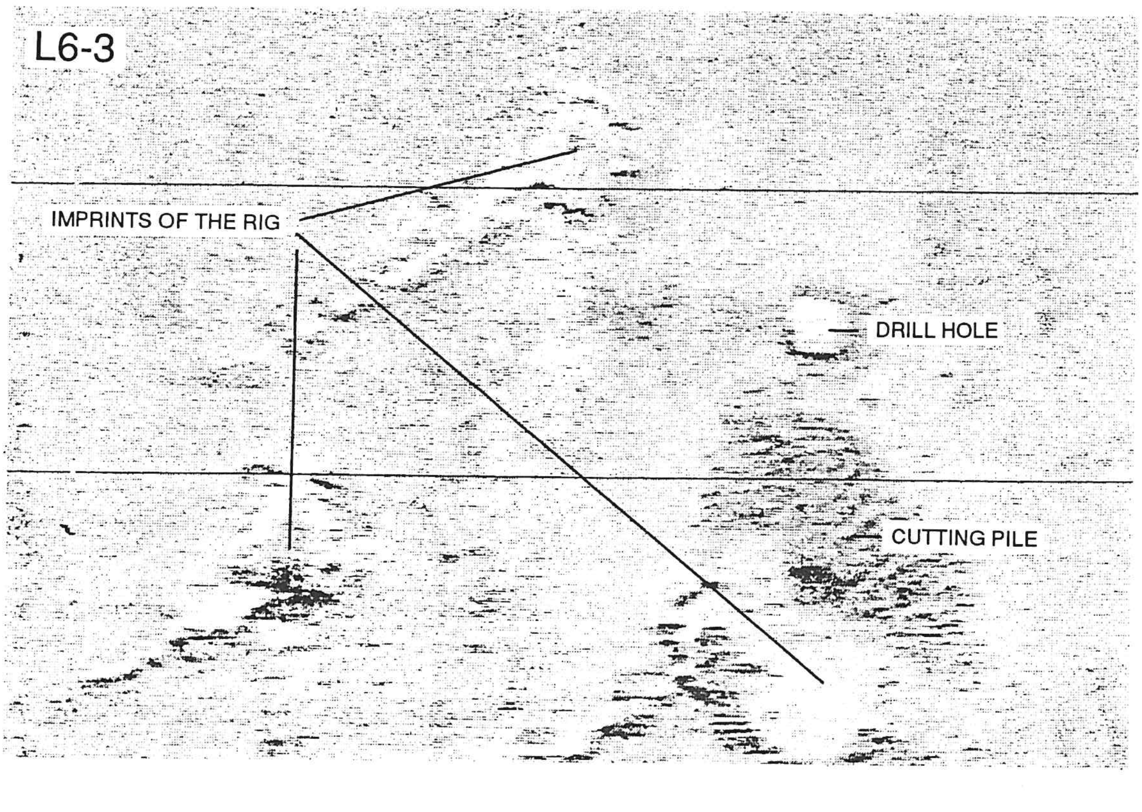
At both locations the sampling stations were chosen along a cross-shaped transect (Fig. 3). One axis of the transect ran parallel with the residual current direction (77°), the other axis perpendicular to the first one. The outermost stations, at 5 km from the discharge site, were assumed to represent a reference situation to which possible spatial effects could be related.

Bottom samples were collected with a 0.2 m^2 Van Veen grab, 8 samples per station. Two additional samples were taken at the very discharge site. From each sample small duplicate cores (diameter 28 mm, depth 10 cm) were taken for chemical and grainsize analyses). Per station these sediment samples were pooled, thoroughly homogenised and immediately frozen at -20°C until later analysis in the laboratory. Then the contents of the grab were washed through a sieve (mesh size 1 mm) and the residual macrofauna was preserved in a 6% neutralized formaldehyde solution.

During sampling on board of the research vessel, the samples of all stations were inspected for the presence of large heart urchins (*Echinocardium cordatum*, specimens >1 cm) and the numbers per sample were counted.

Fig. 2. Side scan sonar records showing the imprints of the rigs at L3-3 and L6-3.


L3-3
IMPRINTS OF THE RIG
DRILL HOLE


L6-3
IMPRINTS OF THE RIG
DRILL HOLE
CUTTING PILE

2.2 LABORATORY ANALYSES

In the laboratory a selection of the macrofauna samples was stained with Bengal rose and sorted using a magnifier. Then molluscs, crustaceans, polychaetes and echinoderms were identified under a stereomicroscope and counted on species level. Remaining taxa were not further identified and only recorded at higher taxonomic levels. When specimens were broken by handling, only heads were counted.

Not all samples were analysed. In Fig. 3 those stations are indicated of which 6 samples each were analysed.

The physico-chemical analyses of sediment samples were performed by IMW-TNO, according to routine methods (see GROENEWOUD & SCHOLTEN, 1992). Grainsize analyses were carried out for all stations at both locations. Barium analyses were performed for all stations sampled around location L3-3, where barite contributed a substantial part of the dumped material. For location L6-3 a selection of stations was made of which the samples were analysed for barium, since, according to the list of dumped drilling chemicals, significantly elevated barium concentrations were not expected here. For both locations the sediment sample taken at the discharge site was used for a check on the absence of base oil in the sediment. Using the GCMS technique the concentrations of the fractions of alkanes (C_{10} - C_{30}), unidentified complex matter (UCM) and "other oil components" were quantified.

2.3 STATISTICAL PROCEDURES

In samples collected over a gradient in disturbance there may be a gradual change in the abundance of individual species over the sampled transect. Statistical analyses are required to obtain objective criteria to decide whether such changes in faunal abundance are significant or not. Such analyses were performed on species level as well as on community level. The methods applied are described in detail by DAAN *et al.* (1990) and are summarized below.

2.3.1 INDIVIDUAL SPECIES (LOGIT REGRESSION)

Logit regression (see JONGMAN *et al.*, 1987) is based on a mathematical model for presence-absence data of individual species in samples collected along a transect with a gradient in pollution. The basic idea is that, if the disturbance involved affects the chance of survival of a certain species, the frequency of occur-

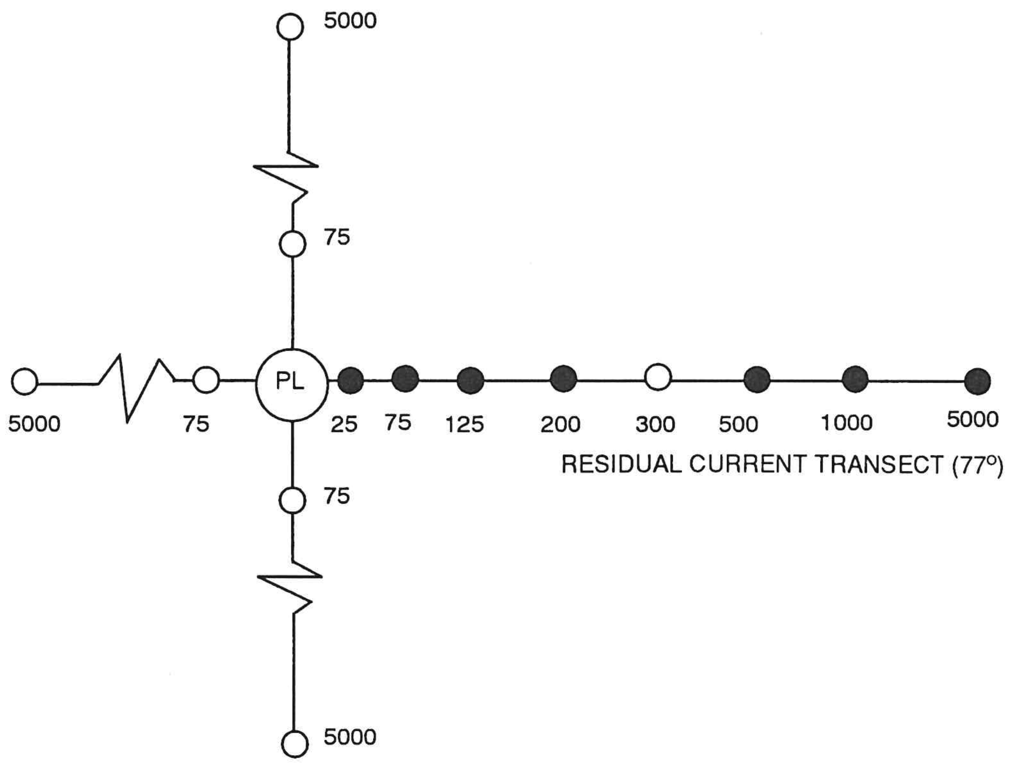


Fig. 3. Positions of the sampling stations (distance to platform in m). The solid circles represent the stations of which a complete fauna analysis was performed.

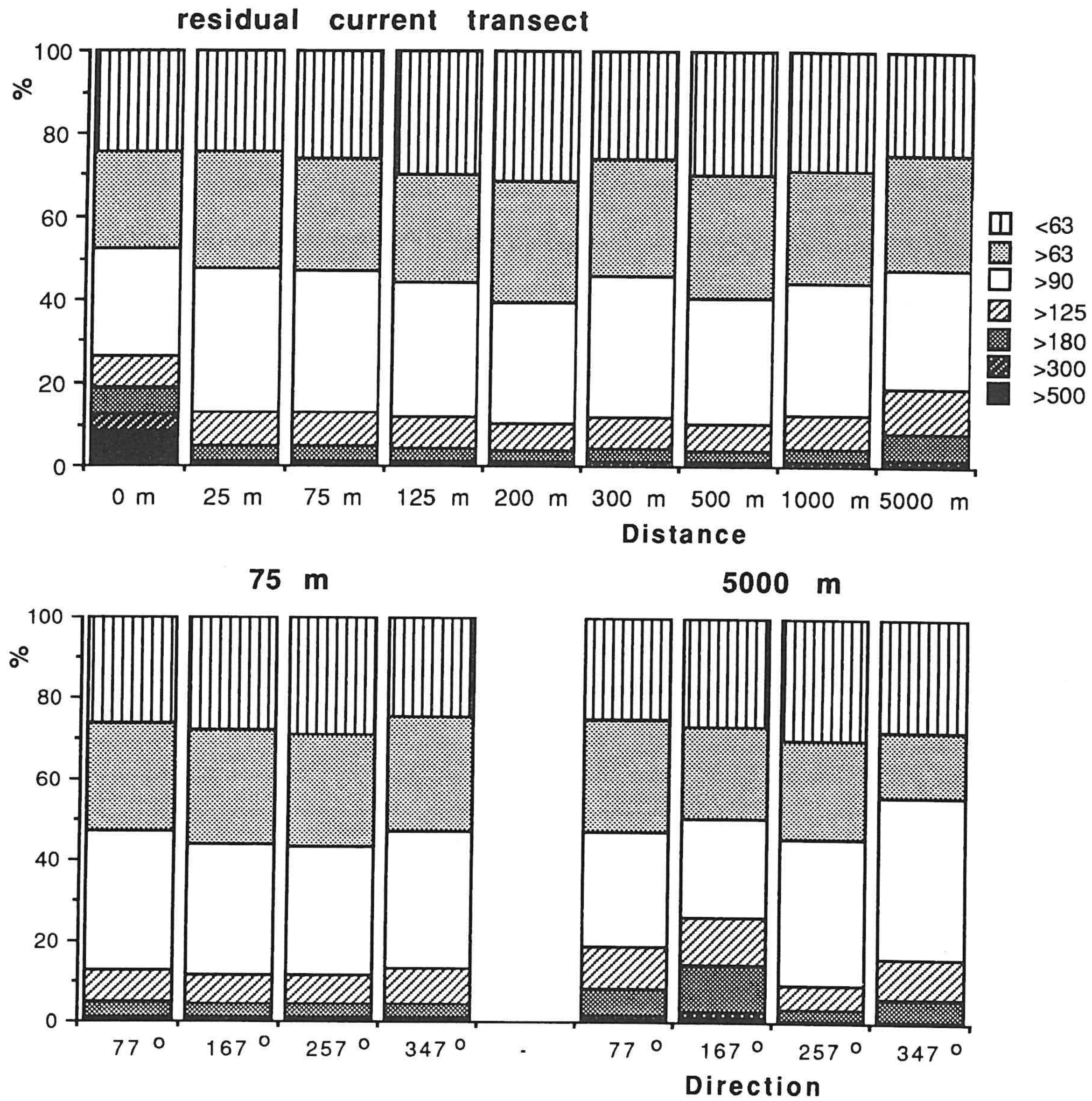


Fig. 4. Location L3-3: Grainsize composition at the stations along the residual current transect (above) and at 75 m and 5000 m in 4 directions (below). Size fractions in μm.

rence of this species will increase or decrease along the transect. In other words, the probability (p) that a species is present in a sample will change along the transect. Logit regression provides a test to decide either that p increases or decreases significantly with distance to the discharge site or that p just fluctuates at random. Logit regression was applied to those species of which at least 20 specimens were found.

2.3.2 MACROBENTHIC COMMUNITY (RELATIVE ABUNDANCE)

This method provides a measure of the mean relative abundance of all identified species at each station, compared to the other stations around a location. For example, if at a certain station most species occur in lower numbers than at other stations, the relative macrofauna abundance at this station will be attrib-

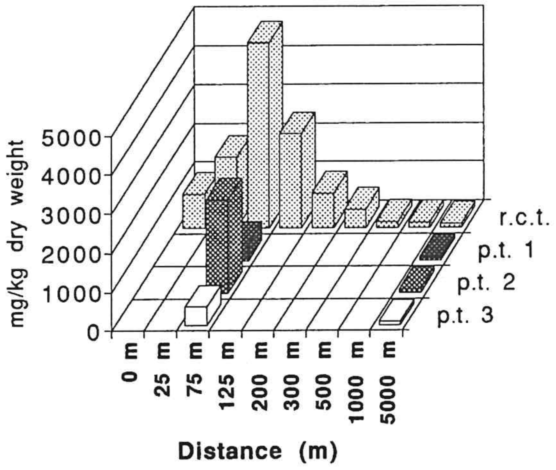


Fig. 5. Location L3-3: Spatial pattern of Ba concentrations in the sediment. r.c.t = residual current transect (77°); p.t. = perpendicular transect.

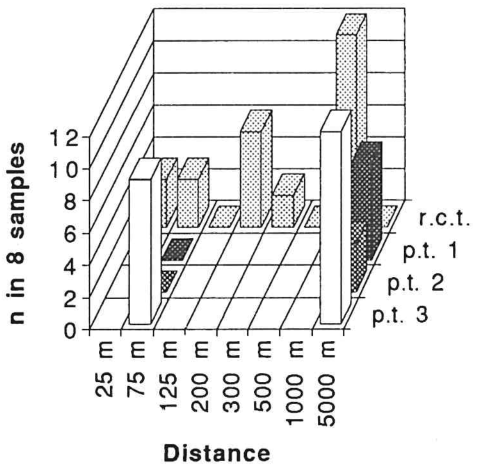


Fig. 7. Location L3-3: Spatial abundance pattern of *Echinocardium cordatum* (number of specimens >1 cm in 8 samples ≈1.6 m^2).

uted a low value. The computation of relative abundance is based on a ranking procedure. For all of the individual species the mean density is considered at each of *n* investigated stations. Per species a rank is attributed to each of the stations: the rank is 1 for the station with the lowest abundance and *n* for the station with the highest abundance. When this procedure is completed for all species a mean rank can be calculated for each station. Differences in mean ranks between stations were tested for significance by applying analysis of variance.

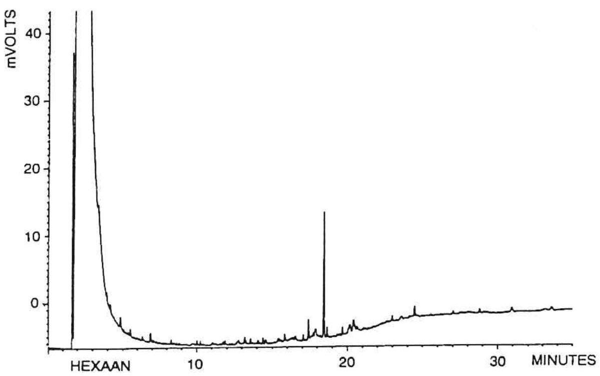


Fig. 6. Location L3-3: GCMS chromatogram of sediment collected at the discharge site.

3 RESULTS

3.1 LOCATION L3-3

3.1.1 PHYSICOCHEMICAL CHARACTERISTICS

During the fieldwork on board of the ship, all Van Veen grab samples were inspected by eye for the presence of drill cuttings. Large amounts of cuttings were only found at the discharge site. The samples taken here appeared to contain hardly any animal life and were not further analysed in the laboratory for macrofauna. At 25 m and the stations at larger distance no cuttings were observed. Apparently, the coarse fraction of the material dumped was still concentrated in a very small area around the discharge site. Fig. 4 confirms that a substantial coarse fraction (>500 µm) was only present at the 0-m station. The grainsize distribution at the other stations reveals that the natural sediment composition was quite homogeneous in the area. The fraction <63 µm fluctuated between 25 and 30%, which illustrates that the sediment was rich in silt.

TABLE 2

Concentrations of oil components (mg·kg^{-1} dry weight) in the sediment at the discharge sites of L3-3 and L6-3.

	L3-3	*L6-3*
UCM	<1.0	5.36
C_{10}-C_{30}	0.37	1.34
others	1.56	5.91
Total oil	<2.93 (background)	12.61 (>background)

TABLE 3
Location L3-3: Percentage occurrence of the macrofauna species in the total number of analysed samples (42).

POLYCHAETA		*Capitella capitata*	4.8	*Ebalia cranchii*	2.4
		Notomastus latericeus	66.7	*Nephrops norvegicus*	2.4
Aphrodite aculeata	4.8	*Heteromastus filiformis*	57.1	*Upogebia stellata*	4.8
Harmothoe ljungmani	4.8	*Owenia fusiformis*	90.5	*Upogebia deltaura*	69.1
Harmothoe lunulata	23.8	*Myriochele oculata*	7.1	*Upogebia* spec. juv.	2.4
Harmothoe longisetis	16.7	*Lanice conchilega*	7.1	*Callianassa subterranea*	100.0
Harmothoe spec. juv.	2.4	*Lagis koreni*	95.2	Decapoda (larvae)	2.4
Gattyana cirrosa	76.2	*Pectinaria auricoma*	100.0	*Nebalia bipes*	9.5
Pholoe minuta	97.6	*Ampharete finmarchica*	9.5	*Gastrosaccus spinifer*	2.4
Sthenelais limicola	11.9	*Amphicteis gunneri*	54.8	*Pseudocuma longicornis*	2.4
Hesionura augeneri	2.4	*Sosane gracilis*	40.5	*Diastylis bradyi*	47.6
Anaitides groenlandica	4.8	*Lysilla loveni*	14.3	*Ione thoracica*	21.4
Anaitides mucosa	2.4	*Terebellides stroemi*	35.7	*Pseudione spec.*	16.7
Anaitides maculata	14.3			*Orchomenella nana*	2.4
Anaitides subulifera	2.4	MOLLUSCA		*Leucothoe incisa*	2.4
Eumida sanguinea	2.4			*Ampelisca brevicornis*	9.5
Ophiodromus flexuosus	61.9	*Nucula turgida*	64.3	*Ampelisca tenuicornis*	71.4
Gyptis capensis	66.7	*Thyasira flexuosa*	2.4	*Ampelisca spec. juv.*	2.4
Synelmis klatti	21.4	*Lepton squamosum*	14.3	*Cheirocratus sundevalli*	2.4
Exogone hebes	14.3	*Devonia perrieri*	9.5	*Harpinia antennaria*	59.5
Nereis longissima	33.3	*Montacuta ferruginosa*	35.7	*Aora typica*	7.1
Nereis spec. juv.	2.4	*Mysella bidentata*	100.0	*Photis longicaudata*	2.4
Nephtys hombergii	50.0	*Arctica islandica*	9.5		
Nephtys incisa	66.7	*Acanthocardia echinata*	7.1	ECHINODERMATA	
Nephtys longosetosa	2.4	*Dosinia lupinus*	7.1		
Nephtys spec. juv.	42.9	*Venus striatula*	11.9	*Amphiura filiformis*	100.0
Glycera rouxii	85.7	*Venus* spec. juv.	2.4	*Amphiura chiajei*	59.5
Glycera alba	11.9	*Mysia undata*	7.1	*Ophiura texturata*	4.8
Glycinde nordmanni	7.1	*Mactra corallina*	4.8	*Ophiura albida*	11.9
Goniada maculata	38.1	*Spisula* spec. juv.	7.1	*Echinocardium cordatum*	54.8
Lumbrineris latreilli	100.0	*Abra tenuis*	4.8	*Cucumaria elongata*	28.6
Lumbrineris fragilis	59.5	*Abra alba*	23.8	*Cucumaria frondosa*	45.2
Orbinia sertulata	14.3	*Abra nitida*	31.0		
Paraonis fulgens	64.3	*Cultellus pellucidus*	14.3	OTHER TAXA	
Spio filicornis	7.1	*Mya truncata*	11.9		
Polydora pulchra	2.4	*Corbula gibba*	33.3	*Nemertinea*	85.7
Polydora guillei	16.7	*Thracia convexa*	31.0	*Nematoda*	7.1
Spiophanes kroyeri	2.4	*Cingula nitida*	92.9	*Turbellaria*	66.7
Spiophanes bombyx	76.2	*Turritella communis*	38.1	*Phoronida*	95.2
Scolelepis foliosa	2.4	*Natica alderi*	38.1	Copepoda (Harpacticoida)	2.4
Magelona alleni	2.4	*Cylichna cilindracea*	57.1	Copepoda (parasites)	2.4
Chaetopterus variopedatus	88.1			Oligochaeta	11.9
Tharyx marioni	19.1	CRUSTACEA		Holothuroidea	11.9
Chaetozone setosa	7.1			Echiurida	35.7
Diplocirrus glaucus	47.6	*Processa parva*	57.1	Sipunculida	92.9
Scalibregma inflatum	88.1	*Macropipus holsatus*	2.4	Anthozoa	2.4
Ophelina acuminata	92.9	*Macropipus spec. juv.*	2.4	Ascidiacea	9.5
				Foraminiferida	2.4

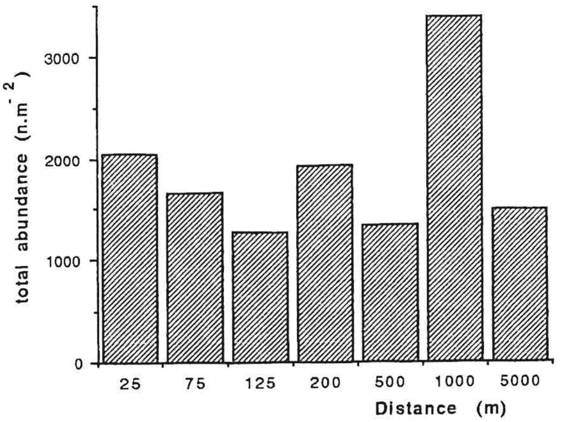


Fig. 8. Location L3-3: Total macrofauna abundance along the residual current transect.

Since a substantial amount of barite was added to the drilling fluids utilised at L3-3, concentrations of barium in the sediment may be used as a tracer for the spatial spread of the small-grainsize fractions in the discharged material. Fig. 5 shows that significant concentrations occurred up to 300 m but even at 500 m and 1000 m the concentrations seemed to be slightly elevated compared to background levels found at 5000 m (90 to 110 mg Ba. kg^{-1} dry sediment). Between 75 m and 1000 m there was a clear gradient of decreasing Ba concentrations. At the discharge site and at 25 m the concentrations were relatively low compared to the 75 m (r.c.) station.

To verify the absence of OBM-contaminated material 1 sediment sample (originating from the discharge site) was analysed for oil. Given the background levels known to be usual in the Dutch sector (2 to 7 mg. kg^{-1} dry sediment, see ZEVENBOOM *et al.*, 1992) the total oil concentration (3.1 mg·kg dry sediment, see

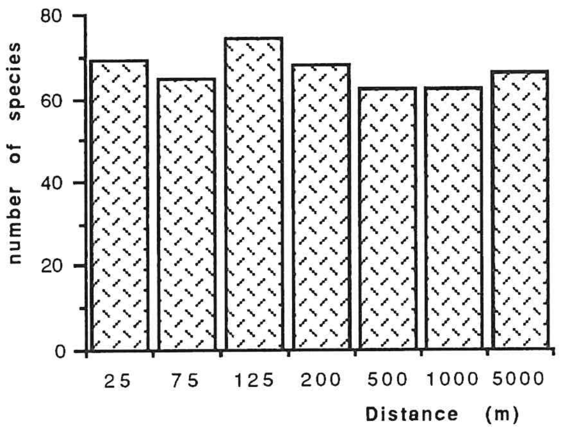


Fig. 9. Location L3-3: Numbers of identified species found at the stations along the residual current transect (in 6 samples per station).

TABLE 4

Location L3-3: List of species for which gradients in frequency of occurrence were tested by logit regression. Sign of the gradient (+/-) and significance level are indicated: + =increasing frequency of occurrence away from the location; - =decreasing frequency of occurrence away from the location; 0 =no gradient.

	sign	*sign. level (%)*
Gattyana cirrosa	-	n.s.
Pholoe minuta	+	n.s.
Ophiodromus flexuosus	-	n.s.
Gyptis capensis	-	n.s.
Nephtys hombergi	-	n.s.
Nephtys incisa	+	n.s.
Glycera rouxii	-	5
Goniada maculata	+	n.s.
Lumbrineris latreilli	0	-
Lumbrineris fragilis	-	5
Paraonis fulgens	-	1
Spiophanes bombyx	+	n.s.
Chaetopterus variopedatus	-	n.s.
Diplocirrus glaucus	+	n.s.
Scalibregma inflatum	-	0.5
Ophelina acuminata	-	n.s.
Notomastus latericeus	+	n.s.
Heteromastus filiformis	+	n.s.
Owenia fusiformis	-	n.s.
Lagis koreni	+	n.s.
Pectinaria auricoma	0	n.s.
Amphicteis gunneri	+	n.s.
Sosane gracilis	-	n.s.
Nucula turgida	+	n.s.
Montacuta ferruginosa	-	n.s.
Mysella bidentata	0	n.s.
Corbula gibba	-	n.s.
Cingula nitida	+	n.s.
Turritella communis	+	n.s.
Natica alderi	+	5
Cylichna cilindracea	-	n.s.
Processa parva	-	n.s.
Upogebia deltaura	-	n.s.
Callianassa subterranea	0	n.s.
Diastylis bradyi	-	n.s.
Ampelisca tenuicornis	-	n.s.
Harpinia antennaria	+	n.s.
Amphiura filiformis	0	n.s.
Amphiura chiajei	-	n.s.
Cucumaria frondosa	+	n.s.

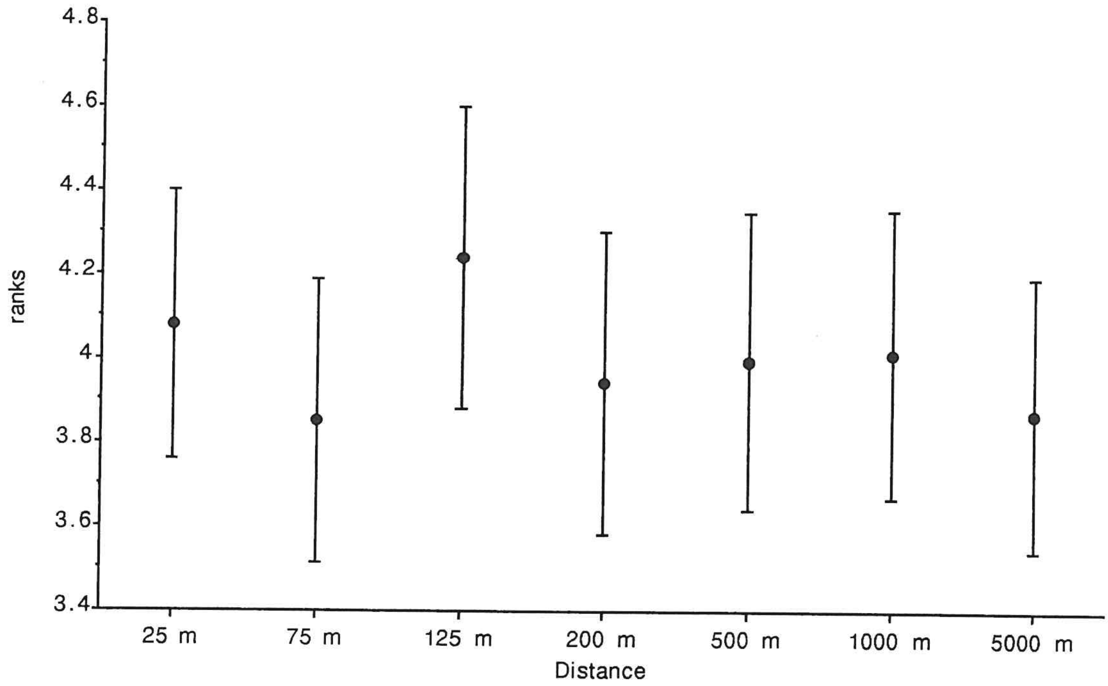


Fig. 10. Location L3-3: Pattern of relative abundance along the residual current transect. Centre points are mean ranks and vertical bars give 95% confidence limits.

Table 2) appeared not to exceed these background levels. The GCMS chromatogram (Fig. 6) lacks a typical UCM hill, which usually appears within 5 to 10 minutes.

3.1.2 GENERAL FAUNA DESCRIPTION

The on board countings of *Echinocardium cordatum*, a species known to respond very sensitive to OBM related cutting discharges, resulted in numbers ranging from 0 to 12 specimens >1 cm per 8 samples (Fig. 7). The abundance pattern does not show any indication for a gradual shift in abundance that is related to distance to the discharge site. Application of logit regression revealed that, indeed, there was no significant gradient. The fluctuation in abundance at the different stations should be properly explained by natural variation.

The laboratory analyses yielded 105 identified macrofauna species. In Table 3 their percentual occurrence in the samples is summarized. The original data are listed in Table 12 (appendix). The fauna in the area was dominated by the echinoderm *Amphiura filiformis* and the mollusc *Mysella bidentata*, a species that is living as a commensal of *Amphiura*. Together these species generally accounted for over 50% of the total macrofauna abundance. To a lesser extent the polychaete *Lumbrineris latreilli* was also abundant. None of these species showed a sign of a gradient in abundance over the sampled transect. Also in the total abundance of the macrofauna at the stations investigated (Fig. 8) there was no consistent spatial gradient or a pattern that could be related to barium concentrations. The fluctuations in the total macrofauna abundance are largely caused by variations in the abundance of *A. filiformis* and *M. bidentata.* Both were extremely abundant at the 1000-m station and occurred in relatively low numbers at the 125-m station. Densities of the dominant and more or less abundant species were consistently in the range of "natural" densities in the Frisian Front area as assessed by HOLTMANN & GROENEWOLD (1992).

The number of identified species at the different stations (Fig. 9) was quite stable, varying between 62 (500 m and 1000 m) and 74 (125 m). These numbers are similar to those found at reference sites in this area in previous studies (see MULDER *et al.*, 1988; DAAN *et al.*, 1990, 1991, 1992). There was neither an indication for a gradual shift in species richness over the sampled transect, nor any relationship between number of species and barium concentrations.

3.1.3 PRESENCE-ABSENCE DATA: LOGIT REGRESSION

Possible gradients in the abundance patterns of individual species were statistically tested by logit regression. This procedure was performed only for those 40 species that were abundant enough (≥20 specimens found) to detect any gradient. The results, listed in Table 4, show that a gradient seemed to be significant (5% level) in 5 species. In 1 species the gradient was positive (increasing frequency of occurrence away from the location) and in 4 species the gradient was negative (decreasing frequency of occurrence away from the location).

If these gradients were an effect of the discharges, this would imply that 1 species suffered from the disturbance and that 4 species took advantage of it and increased in abundance. However, in view of the number of tests it is questionable whether the supposed significance of these gradients is realistic. Since 40 analyses were performed at the 5% level, testing the hypothesis H_0 that there is no gradient in frequency of occurrence, the expected number of statistical Type-1 errors (H_0 is rejected when it is true) is 2. The chance, however, that 5 or more Type-1 errors occur is 5.16%, in other words more than 5%. Hence the odds are not unacceptable that 5 or more Type-1 errors occurred. In 40 tests the number of rejections should be at least 6 (p=1.47% that all are Type-1 errors) to decide that at least 1 gradient is significant at the 5% level. It is concluded therefore that logit regression did not reveal significant gradients among the individual species.

3.1.4 RELATIVE ABUNDANCE

A plot of the relative macrofauna abundance, calculated as the mean of all individual species (Fig. 10), shows that the mean rank of the 7 stations along the residual current transect was consistently close to 4, illustrating that there was no station where, on average, most species were less or more abundant than at other stations. Analysis of variance confirmed that there were no significant differences between the stations.

3.1.5 ABUNDANCE PATTERNS OF OBM-SENSITIVE AND OPPORTUNISTIC SPECIES

In earlier studies on the effects of OBM-related cutting discharges, most carried out in the vicinity of the Frisian Front area, a number of species was found to be susceptible to the sediment contamination involved. Those species were absent or occurred in reduced abundance especially in the vicinity of the well site. A few other species (opportunists) were found to occur in elevated numbers particularly in contaminated sediment. Table 5 shows to what extent the abundance patterns of these species were indicative of sediment pollution at L3-3. Only one OBM-sensitive species (the polychaete *Scalibregma inflatum*) showed a gradual shift in abundance, but, in contrast to OBM locations, high numbers within 500 m from the discharge site and relatively low numbers

TABLE 5

Location L3-3: Evaluation of the abundance patterns of 37 species sensitive to OBM contamination and 4 opportunistic species.
tendency:+= tendency for higher abundance away from the platform
-= tendency for lower abundance away from the platform
0= no tendency for a spatial gradient
(?)= total number of specimens found <20
(Note that the qualifications are based on the abundance patterns of the individual species and not on presence-absence data as used in logit regression)

	tendency
A. species sensitive to OBM contamination	
Montacuta ferruginosa	0
Scalibregma inflatum	-
Pholoe minuta	0
Amphiura filiformis	0
Echinocardium cordatum	0
Mysella bidentata	0
Nephtys hombergi	0
Lumbrineris latreilli	0
Chaetozone setosa	0 (?)
Owenia fusiformis	0
Nucula turgida	0
Gattyana cirrosa	0
Harpinia antennaria	0
Lagis koreni	0
Glycinde nordmanni	0 (?)
Cylichna cilindracea	0
Harmothoe longisetis	0 (?)
Callianassa subterranea	0
Magelona papillicornis	species not found
Tellina fabula	species not found
Natica alderi	0
Spiophanes bombyx	0
Ophiodromus flexuosus	0
Notomastus latericeus	0
Lumbrineris fragilis	0
Amphiura chiajei	0
Leucothoe incisa	0 (?)
Chaetopterus variopedatus	0
Tharyx marioni	0 (?)
Ophiura albida	0 (?)
Gyptis capensis	0
Lanice conchilega	0 (?)
Perioculodes longimanus	species not found
Diplocirrus glaucus	0
Abra alba	0 (?)
Turritella communis	0
Sthenelais limicola	0 (?)
B. opportunistic species	
Nereis longissima	0 (?)
Capitella capitata	- (?)
Spio filicornis	0 (?)
Anaitides groenlandica	0 (?)

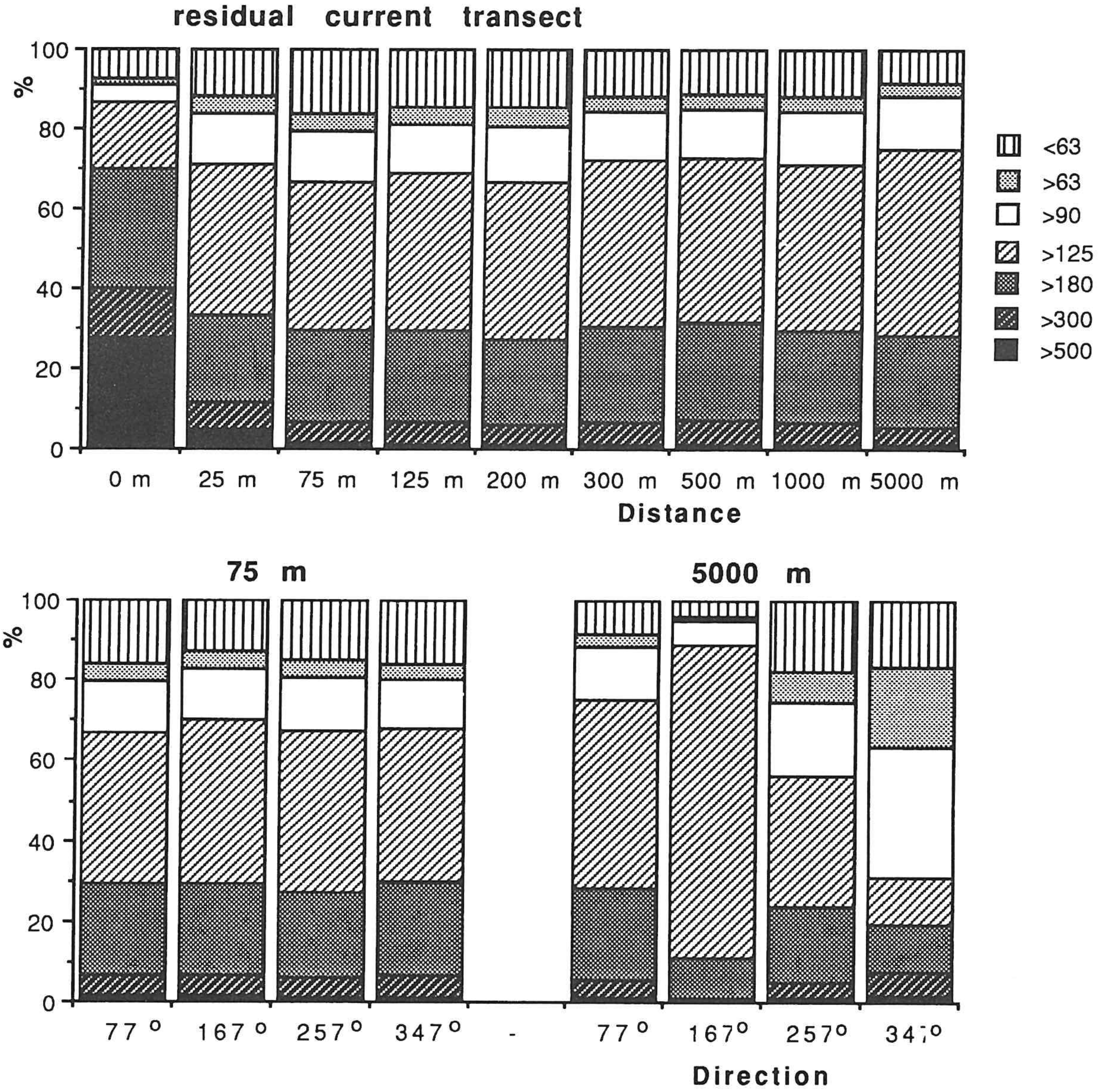


Fig. 11. Location L6-3: Grainsize composition at the stations along the residual current transect (above) and at 75 m and 5000 m in 4 directions (below). Size fractions in mm.

at 1000 m and 5000 m. Hence, there is no reason to consider this shift in abundance as an effect of the dumpings at L3-3. It is more likely that it should be explained as an accidental natural abundance gradient. Among the opportunists the occurrence of *Capitella capitata* at 25 m and 75 m was remarkable. The species is scarce by nature and where it occurs it is highly indicative of organic enrichment of the sediment. Although only 2 specimens were found, the presence of this species may, therefore, still indicate disturbance of the sediment.

3.2 LOCATION L6-3

3.2.1 PHYSICO-CHEMICAL CHARACTERISTICS

During the fieldwork, large amounts of discharged drill cuttings were found in the vicinity of the location.

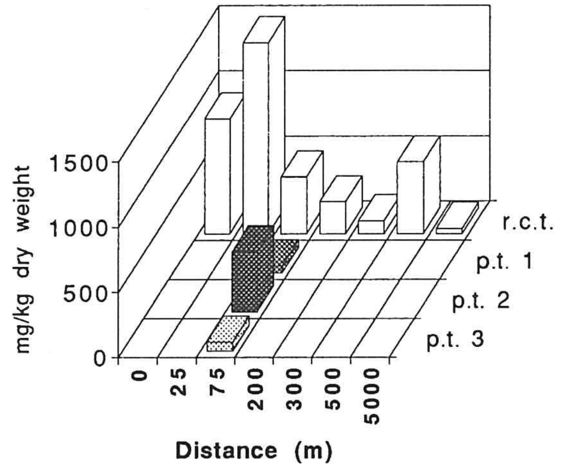


Fig. 12. Location L6-3: Spatial pattern of Ba concentrations in the sediment. r.c.t = residual current transect (77°); p.t. = perpendicular transect.

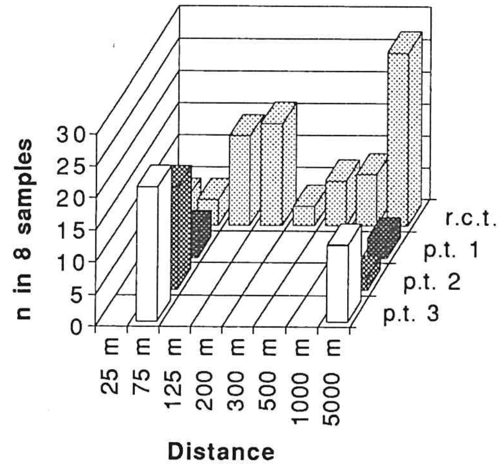


Fig. 14. Location L6-3: Spatial abundance pattern of *Echinocardium cordatum* (number of specimens > 1 cm in 8 samples ≈1.6 m^2).

The 2 samples collected at the discharge site consisted almost completely of cutting material and no fauna was observed here. At the 25-m station a few samples contained large amounts of cuttings, in the other samples only few cuttings were found. At a distance of 75 m some cuttings were found only in the residual current direction.

The grainsize distribution along the residual current transect confirms these visual observations. Fig. 11 shows that a large fraction of coarse material was present particularly at the discharge site (0 m), and, to a lesser extent, at 25 m. The grainsize distribution at the other stations along this transect shows a quite homogeneous natural sediment composition, but the silt fraction (<63 μm) becomes gradually smaller with increasing distance to the location. At the 5000-m stations in the other directions the sediment compositions appeared to be very variable.

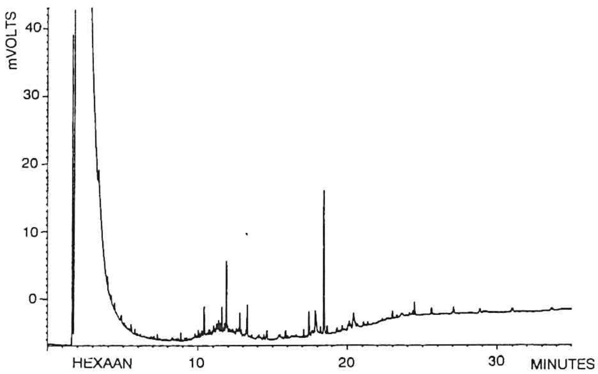


Fig. 13. Location L6-3: GCMS chromatogpram of sediment collected at the discharge site.

Barium concentrations were measured at 7 stations along the residual current transect and at 3 stations at a distance of 75 m in the other directions (Fig. 12). Although the list of drilling chemicals does not include barite, high Ba concentrations were found in the sediment up to 500 m from the discharge site. The concentrations were highest in the vicinity of the discharge site (at 0 m and 25 m) and there was a gradual decrease between 25 m and 300 m to values only slightly exceeding backgroundlevel. At 500 m a substantially elevated concentration was measured again. At 5000 m and 2 of the 75 m stations in perpendicular directions the concentrations were at background level, *i.e.* 40-70 mg·kg^{-1} dry sediment*. The spatial distribution of elevated Ba levels suggests that a substantial amount of Barium must have been dumped at or close to the discharge site.

One sediment sample, collected at the discharge site, was analysed for the presence of oil. The chromatogram (Fig. 13) shows that, between 9 and 14 minutes, a small UCM hill appeared, which is characteristic of OBM base oil. The peaks in this part of the chromatogram indicate the presence of alkanes (C_{10} -C_{30}) and other oil components. The total oil concentration (≈12.6 mg·kg^{-1} dry sediment) appeared to be slightly but significantly elevated compared to background level (always <7 mg·kg^{-1}, see ZEVENBOOM *et al.*, 1992).

**Note that background levels at L6-3 are somewhat lower than at L3-3. This is easily explained by the fact that natural Ba concentrations are strongly correlated with the silt fraction (< 63 μm) of the sediment (Groenewoud & Scholten, 1992). At L6-3 the natural silt fraction is significantly smaller than at L3-3 (see Table 10, appendix).*

TABLE 6

Location L6-3: Percentage occurrence of the macrofauna species in the total number of analysed samples (42).

POLYCHAETA		*Owenia fusiformis*	57.1	*Corystes cassivelaunus*	40.5
		Myriochele oculata	59.5	*Upogebia deltaura*	69.1
Harmothoe lunulata	14.3	*Lanice conchilega*	95.2	*Upogebia* spec. juv.	14.3
Harmothoe longisetis	11.9	*Polycirrus medusa*	7.1	*Callianassa subterranea*	100.0
Harmothoe spec. juv.	19.1	*Lagis koreni*	100.0	Decapoda (larvae)	4.8
Gattyana cirrosa	38.1	*Pectinaria auricoma*	57.1	*Nebalia bipes*	2.4
Pholoe minuta	100.0	*Ampharete finmarchica*	23.8	*Eudorella truncatula*	26.2
Sthenelais limicola	31.0	*Amphicteis gunneri*	23.8	*Iphinoe trispinosa*	2.4
Eteone longa	9.5	*Eupolymnia nebulosa*	4.8	*Diastylis bradyi*	73.8
Eteone spec. juv.	14.3	*Lysilla loveni*	2.4	*Ione thoracica*	40.5
Mysta barbata	7.1			*Pseudione* spec.	2.4
Anaitides groenlandica	23.8	MOLLUSCA		*Melita dentata*	2.4
Anaitides maculata	11.9			*Scopelocheirus hopei*	4.8
Anaitides spec. juv.	31.0	*Nucula turgida*	95.2	*Orchomenella nana*	4.8
Eumida sanguinea	9.5	*Thyasira flexuosa*	16.7	*Leucothoe incisa*	54.8
Syllis spec.	2.4	*Lepton squamosum*	19.1	*Metopa alderi*	2.4
Ophiodromus flexuosus	73.8	*Montacuta ferruginosa*	69.1	*Ampelisca brevicornis*	76.2
Gyptis capensis	71.4	*Mysella bidentata*	100.0	*Ampelisca tenuicornis*	73.8
Exogone hebes	16.7	*Arctica islandica*	7.1	*Bathyporeia guilliamsoni*	7.1
Nereis longissima	42.9	*Acanthocardia echinata*	2.4	*Harpinia antennaria*	76.2
Nereis spec. juv.	64.3	*Dosinia lupinus*	4.8	*Perioculodes longimanus*	2.4
Nephtys hombergii	92.9	*Venus striatula*	45.2	*Synchelidium haplocheles*	4.8
Nephtys incisa	4.8	*Spisula subtruncata*	31.0	*Corophium insidiosum*	7.1
Nephtys cirrosa	9.5	*Spisula elliptica*	9.5		
Nephtys spec. juv.	16.7	*Tellina fabula*	21.4	ECHINODERMATA	
Goniada maculata	42.9	*Tellina tenuis*	26.2		
Lumbrineris latreilli	100.0	*Abra alba*	88.1	*Amphiura filiformis*	100.0
Lumbrineris fragilis	2.4	*Abra nitida*	7.1	*Amphiura chiajei*	90.5
Orbinia sertulata	9.5	*Gari fervensis*	4.8	*Acronida brachiata*	2.4
Poecilochatus serpens	35.7	*Cultellus pellucidus*	19.1	*Ophiura texturata*	16.7
Spio filicornis	7.1	*Mya truncata*	4.8	*Ophiura albida*	11.9
Polydora ciliata	4.8	*Corbula gibba*	19.1	*Ophiura* spec. juv.	42.9
Polydora pulchra	31.0	*Thracia phaseolina*	78.6	*Echinocardium cordatum*	85.7
Polydora guillei	50.0	*Thracia convexa*	4.8		
Spiophanes bombyx	100.0	*Thracia spec. juv.*	2.4	OTHER TAXA	
Magelona alleni	2.4	*Onoba vitrea*	11.9		
Chaetopterus variopedatus	21.4	*Turritella communis*	23.8	Nemertinea	92.9
Tharyx marioni	19.1	*Natica alderi*	88.1	Nematoda	9.5
Chaetozone setosa	28.6	*Cylichna cilindracea*	85.7	Amphioxus	4.8
Diplocirrus glaucus	78.6			Turbellaria	52.4
Scalibregma inflatum	71.4	CRUSTACEA		Phoronida	95.2
Ophelina acuminata	23.8			Oligochaeta	42.9
Capitella capitata	9.5	*Processa parva*	50.0	Echiurida	2.4
Mediomastus gracilis	97.6	*Pontophilus* spec. juv.	2.4	Sipunculida	54.8
Notomastus latericeus	76.2	*Pagurus bernhardus*	2.4	Anthozoa	11.9

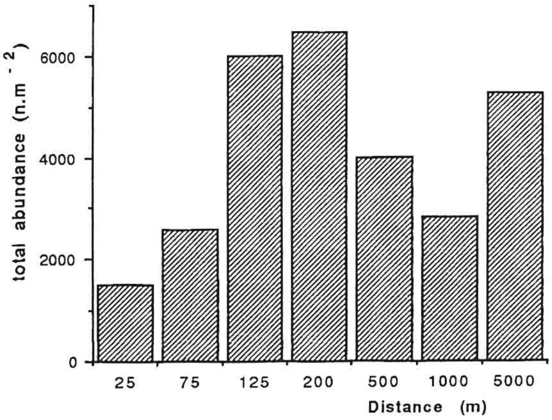


Fig. 15. Location L6-3: Total macrofauna abundance along the residual current transect.

A few additional analyses were performed afterwards by the oil company concerned and resulted in the following concentrations of oil in the sediment ($mg \cdot kg^{-1}$ dry weight):

25 m (r.c.) 20
125 m (r.c.) 12
500 m (r.c.) 9.7
5000 m (167^{o}) 8.8

The data (provided by Marquenie, pers. comm.) confirmed that base oil concentrations were clearly elevated compared to background level up to at least 125 m.

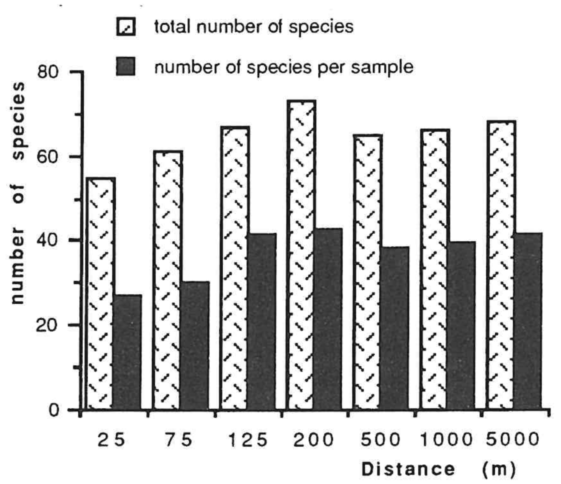


Fig. 16. Location L6-3: Numbers of identified species found at the stations along the residual current transect (in 6 samples per station).

TABLE 7

Location L6-3: List of species for which gradients in frequency of occurrence were tested by logit regression. Sign of the gradient (+/-) and significance level are indicated:
+ =increasing frequency of occurrence away from the location; - =decreasing frequency of occurrence away from the location; 0 =no gradient.

	sign	*sign. level (%)*
Gattyana cirrosa	-	n.s.
Pholoe minuta	0	-
Ophiodromus flexuosus	+	n.s.
Gyptis capensis	-	n.s.
Nereis longissima	-	n.s.
Nephtys hombergii	+	n.s.
Goniada maculata	+	5
Lumbrineris latreilli	0	-
Poecilochaetus serpens	-	n.s.
Polydora guillei	-	0.5
Spiophanes bombyx	0	-
Diplocirrus glaucus	+	n.s.
Scalibregma inflatum	-	n.s.
Mediomastus gracilis	-	5
Notomastus latericeus	+	n.s.
Owenia fusiformis	-	5
Myriochele oculata	+	5
Lanice conchilega	+	0.5
Lagis koreni	0	-
Pectinaria auricoma	+	n.s.
Nucula turgida	+	5
Montacuta ferruginosa	+	n.s.
Mysella bidentata	0	-
Venus striatula	+	5
Spisula subtruncata	+	0.1
Tellina fabula	+	0.5
Tellina tenuis	0	-
Abra alba	+	5
Thracia phaseolina	+	0.5
Natica alderi	+	n.s.
Cylichna cilindracea	-	n.s.
Processa parva	-	n.s.
Corystes cassivelaunus	-	5
Upogebia deltaura	-	0.1
Callianassa subterranea	0	-
Diastylis bradyi	+	n.s.
Ione thoracica	+	n.s.
Leucothoe incisa	+	0.1
Ampelisca brevicornis	-	n.s.
Ampelisca tenuicornis	-	n.s.
Harpinia antennaria	+	0.1
Amphiura filiformis	0	-
Amphiura chiajei	+	0.1

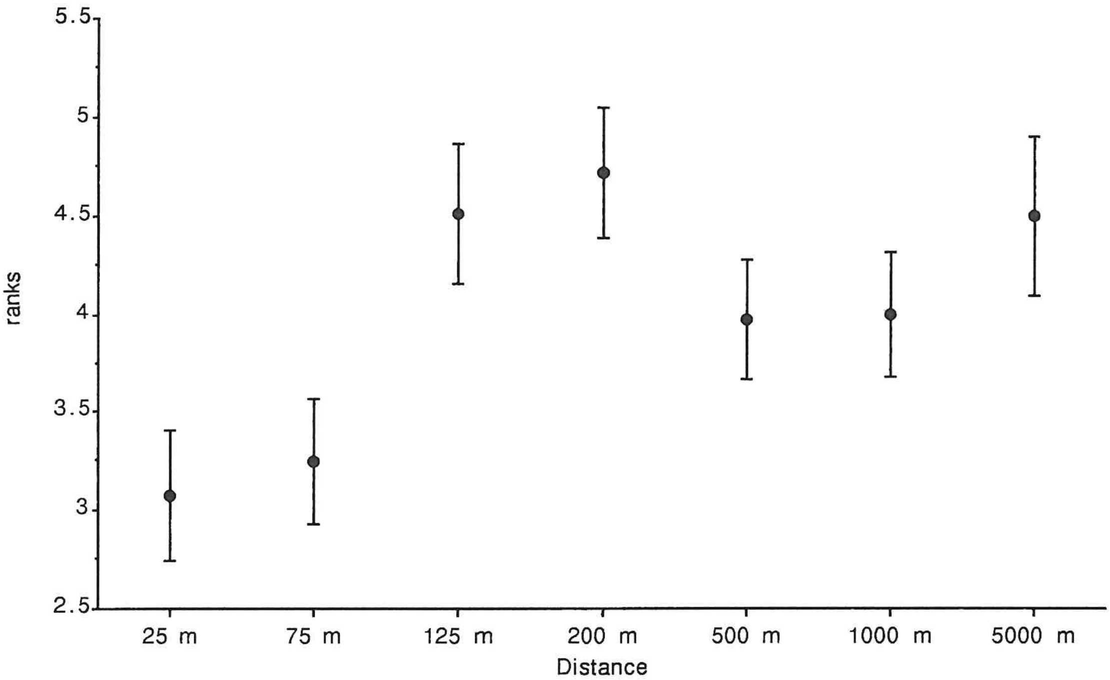


Fig. 17. Location L6-3: Pattern of relative abundance along the residual current transect. Centre points are mean ranks and vertical bars give 95% confidence limits.

3.2.2 GENERAL FAUNA DESCRIPTION

The abundance pattern of large (>1 cm) specimens of *Echinocardium cordatum*, that were counted on board in all samples, does not indicate a gradual shift in abundance related to distance to the well site (Fig. 14). Although in the residual current direction their abundance was lower at the stations within 1000 m than at 5000 m, in the other directions the opposite seemed to be true. Logit regression, applied to verify this visual impression, confirmed that there was no significant relation between numbers of *E. cordatum* in the samples and distance to the location.

A total number of 100 species were identified during this survey. Their percentual occurrence in the samples is summarized in Table 6 (original data in Table 13, appendix). The fauna was dominated by the polychaete *Spiophanes bombyx*, the bivalve mollusc *Mysella bidentata* and the echinoderm *Amphiura filiformis*. Together these species accounted for 63 - 78% of the macrofauna. They all tended to decrease in abundance within 100 m from the discharge site. Particularly at the 25-m station they occurred in low numbers. A majority of the other abundant species, *i.e.* those which occurred in natural densities ≥10 ind·m^{-2}, showed a similar trend as these dominant species, with generally slightly reduced numbers at 75 m and severely reduced numbers at 25 m. Outside

TABLE 8
Location L6-3: Statistical significance (LSD test) of differences in relative macrofauna abundance between stations sampled at the residual current transect. Significance level (%) indicated.

	25 m	*75 m*	*125 m*	*200 m*	*500 m*	*1000 m*	*5000 m*
25 m	.						
75 m	n.s.	.					
125 m	0.1	0.1	.				
200 m	0.1	0.1	n.s.	.			
500 m	0.1	1	5	0.5	.		
1000 m	0.1	0.5	5	1	n.s.	.	
5000 m	0.1	0.1	n.s.	n.s.	5	n.s.	.

100 m their densities were generally in the range of "natural" densities in the Frisian Front area as assessed by HOLTMANN & GROENEWOLD (1992).

The total macrofauna abundance (Fig.15) was obviously low at the 25-m station (less than 1500 ind·m^{-2}) when compared to all other stations (always more than 2500. ind·m^{-2}). Also at 75 m the numbers of individuals seemed to be low, but on the other hand hardly less than at 1000 m. Hence, the total abundance at this station can not be considered as outside the range of natural variation.

The numbers of identified species between 125 m and 5000 m fluctuated within a narrow range of 65 to 73 species per station found (Fig. 16). In the vicinity of the discharge site the numbers (per 8 samples) decreased to 61 at the 75-m station and 55 at the 25-m station. This reduction in species richness becomes even more evident, when the mean number of species per sample is considered, which varied between 38 and 43 at the stations 125 m to 5000 m and dropped to 30 at 75 m and 27 at 25 m.

3.2.3 PRESENCE-ABSENCE DATA: LOGIT REGRESSION

Possible gradients in the abundance patterns of individual species were tested by logit regression. The procedure was performed for 43 species, of which at least 20 specimens were found each. As Table 7 shows, logit regression revealed that 17 species showed a significant (5% level) gradient in their spatial frequency of occurrence. This number is much higher than expected if H_0 (a gradient is not present) were true for all species tested. Moreover, the fact that 12 gradients were positive (increasing frequency of occurrence away from the location) provides strong evidence, that these spatial changes in abundance cannot be considered as accidental natural gradients. In most cases the slope coefficient of the fitted curve was high, indicating that the change in abundance took place over a small part of the sampled transect, generally the part between 0 and 100 m.

3.2.4 RELATIVE MACROFAUNA ABUNDANCE

A plot of the relative macrofauna abundance (Fig. 17) clearly shows that most species occurred in relatively low abundance at 25 m and 75 m from the discharge site. Analysis of variance revealed highly significant ($P<0.001$) differences in mean relative abundance of the different stations. A least significant difference test (LSD-test, see SOKAL & ROHLF, 1981) was subsequently applied to all pairs (21) of means to detect whether they were significantly different (Table 8). The test showed that the 25-m and 75-m stations were not mutually different, but these stations were both significantly (1% level) different from all other stations.

TABLE 9

Location L6-3: Evaluation of the abundance patterns of 37 species sensitive to OBM contamination and 4 opportunistic species.
tendency: += tendency for higher abundance away from the platform
-= tendency for lower abundance away from the platform
0= no tendency for a spatial gradient
(?)= total number of specimens found <20
distance: radius of affected abundance
(Note that the qualifications are based on the abundance patterns of the individual species and not on presence-absence data as used in logit regression)

	tendency	*distance*
A. Species vulnerable to OBM contamination		
Montacuta ferruginosa	+	75 m
Scalibregma inflatum	+	25 m
Pholoe minuta	0	
Amphiura filiformis	+	25 m
Echinocardium cordatum	+	75 m
Mysella bidentata	0	
Nephtys hombergi	0	
Lumbrineris latreilli	0	
Chaetozone setosa	0 (?)	
Owenia fusiformis	0	
Nucula turgida	+	75 m
Gattyana cirrosa	0	
Harpinia antennaria	+	75 m
Lagis koreni	0	
Glycinde nordmanni	species not found	
Cylichna cilindracea	0	
Harmothoe longisetis	0 (?)	
Callianassa subterranea	0	
Magelona papillicornis	species not found	
Tellina fabula	+	200 m
Natica alderi	0	
Spiophanes bombyx	+	25 m
Ophiodromus flexuosus	+	25 m
Notomastus latericeus	0	
Lumbrineris fragilis	0 (?)	
Amphiura chiajei	+	25 m
Leucothoe incisa	0	
Chaetopterus variopedatus	0 (?)	
Tharyx marioni	0 (?)	
Ophiura albida	0 (?)	
Gyptis capensis	0	
Lanice conchilega	+	25 m
Perioculodes longimanus	0 (?)	
Diplocirrus glaucus	+	25 m
Abra alba	+	75 m
Turritella communis	0 (?)	
Sthenelais limicola	0 (?)	
B. opportunistic species		
Nereis longissima	-	500 m
Capitella capitata	- (?)	125 m
Spio filicornis	- (?)	25 m
Anaitides groenlandica	+ (?)	200 m

3.2.5 ABUNDANCE PATTERNS OF OBM-SENSITIVE AND OPPORTUNISTIC SPECIES

In Table 9 (A) 37 species are listed, which in earlier studies at locations where OBM cuttings had been dumped have shown to suffer from those discharges. All these species were inspected for their spatial abundance pattern at L6-3 and the results are listed in this Table. The table shows that, at L6-3 none of these species showed a tendency for higher abundance close to the discharge site. 24 Species did not show any tendency (or were too scarce to detect a gradient), but 13 species occurred obviously in reduced abundance in the vicinity of the location. For most of these species the radius of the area of low abundance did not exceed 50 m (low abundance only at 25 m) or 100 m (low abundance only at 25 m and 75 m). A fine example of the latter group is the amphipod *Harpinia antennaria* (for its numerical abundance at the different stations, see Table 12, appendix). In a previous study at another location in the Frisian Front area this species appeared to respond extremely sensitive to discharged OBM cuttings (DAAN *et al.*, 1990). In one species, the bivalve mollusc *Tellina fabula*, the population densities were low up to 200 m, but there is no convincing evidence that this should be explained as an indication of environmental stress up to this distance. The presence of an accidental natural gradient seems a more plausible explanation for the spatial abundance pattern of this species.

In Table 9 (part B) 4 species are listed, which often have shown to take profit from disturbed conditions around OBM locations and increased in abundance at those sites. At L6-3, three of these species occurred in elevated numbers indeed in the vicinity of the discharge site. In particular the presence of *Capitella capitata* up to 125 m from the location is indicative of organic enrichment of the sediment. In 2 other species (*Nereis longissima* and *Anaitides groenlandica*) accidental natural gradients may have interfered with possible effects of the discharges at L6-3, since these species are not known to be sensitive indicators of sediment contamination. Moreover, the sign of the gradient shown by *Anaitides groenlandica* is in contrast to the expected response of an opportunistic species.

4 DISCUSSION

At L3-3 significant biological effects were not found, not even at 25 m, where physical smothering by a layer of cuttings on the sediment was anticipated. However, coarse material consisting of compressed clay cuttings was found only in a very small area (radius <25 m) around the discharge site. The result indicates that dumping of WBM with a composition like that used at L3-3 does not involve adverse effects on the benthic community. The only slight indication of some disturbance was the presence of a few specimens of *Capitella capitata* at the 25-m and 75-m stations. If, indeed, the presence of this species is an effect of sediment pollution, it seems plausible that the period elapsed since the discharges were terminated has been too short to build up a substantial population. Likewise it should not be excluded that also for other species, which could experience adverse effects from the disturbance, the period has been too short to show a measurable response. It is recommended therefore to carry out a follow-up survey at the longer term to verify the absence of adverse effects.

At L6-3 the situation was quite different. Here the benthic fauna appeared to be significantly affected up to 75 m. The effects could be demonstrated both by community based parameters and spatial abundance patterns of individual species. At 25 m the effects were obviously more severe than at 75 m. In contrast to L3-3 coarse cuttings were found at L6-3 at 25 m as well as at 75 m, but the amounts were not so high, that suffocation of the fauna will have played a major role. Particularly at 75 m a suffocation effect can be definitely excluded. This might suggest that, therefore, the WBM utilised at L6-3 should not be considered harmless and was responsible for the effects observed. However, this conclusion is hampered by the fact that the sediment was not only contaminated with WBM. Traces of oil in the sediment, although in a very low concentration, could be definitely assessed. Moreover, unexpectedly high Ba concentrations, particularly in the residual current direction of the discharge site, suggest that other substances than mentioned in Table 1 have found their way to the seabed at or close to the discharge site of L6-3. The origin of the oil could be clarified afterwards (Marquenie, pers. comm.): it was established that the pipes on board of the drilling rig used at L6-3 had been used previously for OBM drilling at another location in the Dutch sector. Since the pipes were not cleaned up before they arrived at L6-3, the WBM will have been contaminated with a certain amount of base oil. An estimate of 5-10 litres, based on a theoretical calculation, may be approximately realistic. It was also confirmed afterwards that the chromatogram of the oil found in the sediment corresponded with the fingerprint of this base oil. Hence, the use of oil contaminated pipes seems to be the most likely explanation for the presence of oil in the sediment.

Initially, there was good reason to explain the elevated Ba concentrations in a similar way, since barite was also utilized in the previous OBM drilling mentioned. However, further inspection of the information available about the extent of the contamination of the service pipes, revealed that the amount of barium will not have exceeded 0.5 ton. This amount is too small to explain the level of Ba concentrations at L6-3, that were roughly of the same order as those found at L3-3, where the amount of barite known to have been dumped was 470 tonnes (Table 11, appendix). Also when it was assumed that 0.5 ton of barite was dumped at L6-3 and that the material was spread over a narrow strip between 0 and 500 m in the residual current direction from the discharge site, it was impossible to explain the level of concentrations in the sediment.

Because of the presence of barite and, particularly, oil in the sediment it is not possible to assess to what extent the dumping of the WBM cuttings contributed to the effects observed at 25 m and 75 m. The fact that a number of species known to respond sensitive to OBM related discharges appeared to occur in reduced densities at these stations, may point at a significant role of the oil in the sediment, but a decisive answer can not be given. On the other hand, the absence of significant effects at 125 m suggests that the area of environmental impact did not exceed a radius of ≈100 m. This implies that possible effects of the WBM cutting discharges did not occur beyond this distance. In this respect it is concluded that, at the short term, the spatial extent of WBM related discharges is much smaller than usually found for OBM cuttings. *E.g.* at location L5-5 (also in the Frisian Front area), where washed OBM cuttings were discharged in 1988 and a relatively small amount of 44 tonnes of base oil reached the seabed, considerable effects could be assessed up to at least 250 m, whereas subtle indications of environmental stress could be observed up to ≈2 km (DAAN *et al.*, 1991, 1992).

DAVIES *et al.* (1984) already stated that the extent of biological effects is greater from OBM cuttings than from WBM cuttings, but detailed estimates of the spatial extent of WBM induced effects are scarce. HARTLEY & FERBRACHE (1983) concluded from their studies in the Forties (UK sector) that "some localized disturbance to the environment" could occur and DAVIES *et al.* (1984) stated, that there may be a zone of smothering extending out to perhaps 200 m, in which there are major changes in the benthos, but beyond 500 m no changes in benthic populations have been recorded. The latter authors noticed that in most cases surveys have concentrated on the area beyond the 500 m safety zone. Our observations support the idea that biological effects should not be expected beyond this area. For future WBM effect studies it is recommended therefore to use a smaller scaled sampling grid than usually planned in OBM studies.

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APPENDIX

TABLE 10

Grainsize fractions (%) of the sediments around L3-3 and L6-3 (Data provided by IMW-TNO den Helder).

	grainsize:	*>500 μ*	*>300 μ*	*>180 μ*	*>125 μ*	*>90 μ*	*>63 μ*	*<63 μ*
L3-3	0 m	8.8	3.8	6.4	7.3	26.0	23.5	24.2
	25 m 77°	0.3	0.9	3.6	8.2	34.5	28.0	24.5
	75 m 77°	0.3	0.8	3.7	8.0	34.4	26.6	26.1
	125 m 77°	0.3	0.8	3.4	7.3	32.3	26.3	29.5
	200 m 77°	0.3	0.7	2.8	6.4	29.3	28.9	31.7
	300 m 77°	0.2	0.8	3.3	7.4	34.4	28.2	25.6
	500 m 77°	0.3	0.7	2.9	6.5	30.0	29.8	29.8
	1000 m 77°	0.2	0.7	3.6	7.8	31.9	27.0	28.9
	5000 m 77°	0.4	1.4	6.5	10.8	28.2	27.8	25.0
	75 m 167°	0.3	0.8	3.2	7.5	32.3	28.3	27.5
	5000 m 167°	0.9	1.8	11.7	11.7	24.2	23.3	26.7
	75 m 257°	0.3	0.8	3.4	7.3	31.6	27.8	28.8
	5000 m 257°	0.3	0.5	2.4	6.3	35.9	24.5	30.1
	75 m 347°	0.2	0.7	3.8	8.7	33.9	28.5	24.2
	5000 m 347°	0.2	0.3	5.7	9.8	40.1	15.9	27.8
L6-3	0 m	27.6	12.2	30.0	16.7	4.7	1.7	7.2
	25 m 77°	4.8	6.6	22.2	37.7	12.5	4.4	11.8
	75 m 77°	1.4	5.4	22.4	37.7	12.5	4.7	16.0
	125 m 77°	1.2	5.3	22.7	39.6	12.4	4.5	14.4
	200 m 77°	1.2	4.9	20.9	39.8	13.5	5.1	14.7
	300 m 77°	1.3	5.6	23.4	41.8	12.4	4.0	11.5
	500 m 77°	1.3	6.0	24.4	41.0	12.5	3.7	11.1
	1000 m 77°	1.2	5.5	22.5	42.1	13.0	4.3	11.5
	5000 m 77°	1.1	4.5	22.5	46.9	13.3	3.5	8.3
	75 m 167°	1.4	5.4	22.6	40.6	12.9	4.2	13.0
	5000 m 167°	0.4	0.9	9.6	78.0	6.0	1.3	3.7
	75 m 257°	1.2	4.7	21.4	40.0	13.4	4.6	14.6
	5000 m 257°	1.1	3.7	19.1	32.3	18.2	7.7	17.9
	75 m 347°	1.3	5.6	22.9	38.0	12.3	4.0	15.9
	5000 m 347°	1.9	5.9	11.3	11.8	32.4	20.3	16.4

TABLE 11

Barium concentrations (mg·kg^{-1} dry weight) in the sediment around drilling sites L3-3 and L6-3 (Data provided by IMW-TNO den Helder). n.m. = not measured.

station	*L3-3*	*L6-3*
0 m	860	880
25 m r.c.	1830/1830	1460
75 m r.c.	4760	440
125 m r.c.	2410	n.m.
200 m r.c.	890	240
300 m r.c.	460	101
500 m r.c.	150	550
1000 m r.c.	130	n.m.
5000 m r.c.	101	40
75 m 167°	440	55
75 m 257°	2380	460
75 m 347°	490	68
5000 m 167°	93	n.m.
5000 m 257°	110	n.m.
5000 m 347°	90	n.m.

Appendix Table 12. Data location L3-3, residual current, survey Oct. 1991.
Number of analysed samples per station: 6.
Number of identified species.
Mean densities ($n.m^{-2}$).
Tot. number of ind. per m^2 per station.
Number of samples ( ) in which species are present.

Distance to discharge site (m)	25	75	125	200	500	1000	5000
POLYCHAETA							
Aphrodita aculeata	.8 (1)	--	--	--	--	--	.8 (1)
Harmothoe ljungmani	.8 (1)	--	.8 (1)	--	--	--	--
Harmothoe lunulata	1.7 (2)	1.7 (2)	2.5 (2)	1.7 (1)	.8 (1)	1.7 (2)	--
Harmothoe longisetis	1.7 (2)	1.7 (2)	.8 (1)	--	.8 (1)	--	.8 (1)
Harmothoe spec. juv.	--	--	--	--	--	.8 (1)	--
Gattyana cirrosa	5.8 (5)	5.0 (3)	5.8 (3)	27.5 (6)	21.7 (6)	11.7 (6)	5.8 (3)
Pholoe minuta	80.8 (5)	51.7 (6)	41.7 (6)	63.3 (6)	48.3 (6)	82.5 (6)	76.7 (6)
Sthenelais limicola	--	2.5 (2)	.8 (1)	--	.8 (1)	--	.8 (1)
Hesionura augeneri	.8 (1)	--	--	--	--	--	--
Anaitides groenlandica	--	--	.8 (1)	--	--	--	.8 (1)
Anaitides mucosa	--	--	--	.8 (1)	--	--	--
Anaitides maculata	--	.8 (1)	--	.8 (1)	--	1.7 (2)	1.7 (2)
Anaitides subulifera	--	--	.8 (1)	--	--	--	--
Eumida sanguinea	--	--	.8 (1)	--	--	--	--
Ophiodromus flexuosus	1.7 (2)	2.5 (3)	7.5 (5)	3.3 (4)	5.8 (4)	5.8 (5)	2.5 (3)
Gyptis capensis	8.3 (4)	4.2 (2)	10.0 (5)	5.0 (5)	6.7 (5)	4.2 (3)	5.0 (4)
Synelmis klatti	.8 (1)	.8 (1)	.8 (1)	2.5 (3)	--	1.7 (2)	.8 (1)
Exogone hebes	1.7 (2)	--	.8 (1)	.8 (1)	1.7 (1)	--	.8 (1)
Nereis longissima	1.7 (2)	.8 (1)	1.7 (1)	.8 (1)	2.5 (3)	3.3 (3)	3.3 (3)
Nereis spec. juv.	.8 (1)	--	--	--	--	--	--
Nephtys hombergii	5.0 (5)	8.3 (5)	.8 (1)	3.3 (2)	.8 (1)	7.5 (4)	3.3 (3)
Nephtys incisa	8.3 (4)	2.5 (2)	6.7 (4)	8.3 (6)	7.5 (4)	5.8 (3)	5.8 (5)
Nephtys longosetosa	--	1.7 (1)	--	--	--	--	--
Nephtys spec. juv.	4.2 (3)	3.3 (4)	1.7 (2)	2.5 (3)	2.5 (3)	--	3.3 (3)
Glycera rouxii	7.5 (6)	7.5 (4)	6.7 (5)	10.8 (6)	7.5 (6)	10.0 (6)	4.2 (3)
Glycera alba	.8 (1)	--	.8 (1)	--	.8 (1)	--	1.7 (2)
Glycinde nordmanni	--	1.7 (1)	--	.8 (1)	--	--	.8 (1)
Goniada maculata	2.5 (2)	.8 (1)	2.5 (3)	.8 (1)	5.0 (5)	1.7 (1)	3.3 (3)
Lumbrineris latreilli	105.0 (6)	90.8 (6)	85.0 (6)	75.0 (6)	75.8 (6)	145.0 (6)	69.2 (6)
Lumbrineris fragilis	15.8 (6)	5.8 (4)	2.5 (3)	4.2 (3)	5.0 (4)	9.2 (4)	2.5 (1)
Orbinia sertulata	.8 (1)	.8 (1)	.8 (1)	2.5 (2)	--	.8 (1)	--
Paraonis fulgens	10.0 (5)	6.7 (3)	15.0 (6)	3.3 (3)	15.0 (5)	6.7 (4)	.8 (1)
Spio filicornis	--	1.7 (2)	.8 (1)	--	--	--	--
Polydora pulchra	--	--	--	.8 (1)	--	--	--
Polydora guillei	.8 (1)	4.2 (2)	--	.8 (1)	1.7 (1)	1.7 (2)	--
Spiophanes kroyeri	--	--	--	--	.8 (1)	--	--
Spiophanes bombyx	21.7 (6)	13.3 (5)	22.5 (5)	1.7 (2)	6.7 (5)	7.5 (4)	22.5 (5)
Scolelepis foliosa	--	--	.8 (1)	--	--	--	--
Magelona alleni	--	--	.8 (1)	--	--	--	--
Chaetopterus variopedatus	10.0 (6)	5.8 (4)	10.8 (4)	28.3 (6)	22.5 (6)	15.0 (6)	9.2 (5)
Tharyx marioni	1.7 (2)	--	1.7 (1)	2.5 (2)	--	2.5 (3)	--
Chaetozone setosa	--	--	.8 (1)	--	1.7 (1)	.8 (1)	--
Diplocirrus glaucus	3.3 (2)	5.0 (4)	.8 (1)	6.7 (4)	1.7 (2)	3.3 (4)	3.3 (3)
Scalibregma inflatum	13.3 (6)	14.2 (6)	10.8 (6)	10.0 (6)	15.0 (6)	7.5 (4)	2.5 (3)
Ophelina acuminata	31.7 (4)	46.7 (6)	110.0 (6)	35.0 (6)	65.8 (6)	23.3 (6)	14.2 (5)
Capitella capitata	.8 (1)	.8 (1)	--	--	--	--	--
Notomastus latericeus	4.2 (4)	.8 (1)	15.0 (5)	4.2 (4)	32.5 (6)	5.0 (3)	10.8 (5)
Mediomastus gracilis	3.3 (2)	3.3 (3)	6.7 (4)	10.0 (5)	15.0 (4)	2.5 (2)	5.0 (4)
Owenia fusiformis	9.2 (6)	10.0 (5)	10.0 (6)	13.3 (6)	19.2 (6)	14.2 (4)	13.3 (5)
Myriochele oculata	--	--	--	--	--	1.7 (1)	2.5 (2)
Lanice conchilega	2.5 (2)	--	.8 (1)	--	--	--	--
Lagis koreni	33.3 (5)	26.7 (6)	25.0 (5)	18.3 (6)	44.2 (6)	35.8 (6)	60.0 (6)
Pectinaria auricoma	30.8 (6)	41.7 (6)	28.3 (6)	21.7 (6)	22.5 (6)	16.7 (6)	36.7 (6)
Ampharete finmarchica	--	.8 (1)	.8 (1)	--	--	.8 (1)	.8 (1)

Table 12. continued.

Distance to discharge site (m)	25	75	125	200	500	1000	5000
Amphicteis gunneri	2.5 (1)	4.2 (2)	8.3 (4)	4.2 (3)	19.2 (5)	5.0 (5)	4.2 (3)
Sosane gracilis	5.0 (4)	9.2 (4)	3.3 (3)	2.5 (1)	.8 (1)	4.2 (2)	1.7 (2)
Lysilla loveni	--	--	2.5 (3)	.8 (1)	5.0 (2)	--	--
Terebellides stroemi	2.5 (3)	--	2.5 (2)	.8 (1)	5.0 (5)	1.7 (1)	2.5 (3)
MOLLUSCA							
Nucula turgida	5.0 (2)	5.8 (5)	10.8 (5)	2.5 (3)	2.5 (3)	5.8 (3)	10.8 (6)
Thyasira flexuosa	--	.8 (1)	--	--	--	--	--
Lepton squamosum	--	.8 (1)	.8 (1)	--	1.7 (2)	2.5 (1)	.8 (1)
Devonia perrieri	--	.8 (1)	.8 (1)	--	--	--	1.7 (2)
Montacuta ferruginosa	2.5 (1)	2.5 (2)	4.2 (4)	1.7 (2)	--	17.5 (5)	.8 (1)
Mysella bidentata	432.5 (6)	358.3 (6)	176.7 (6)	330.0 (6)	192.5 (6)	937.5 (6)	336.7 (6)
Arctica islandica	1.7 (2)	--	--	--	1.7 (2)	--	--
Acanthocardia echinata	--	.8 (1)	.8 (1)	--	.8 (1)	--	--
Dosinia lupinus	--	--	--	1.7 (2)	.8 (1)	--	--
Venus striatula	.8 (1)	--	3.3 (3)	.8 (1)	--	--	--
Venus spec. juv.	--	--	--	--	.8 (1)	--	--
Mysia undata	.8 (1)	--	--	.8 (1)	.8 (1)	--	--
Mactra corallina	--	--	--	--	--	--	4.2 (2)
Spisula spec. juv.	--	--	--	.8 (1)	.8 (1)	--	.8 (1)
Abra tenuis	2.5 (1)	--	.8 (1)	--	--	--	--
Abra alba	.8 (1)	5.0 (3)	.8 (1)	2.5 (2)	1.7 (1)	--	1.7 (2)
Abra nitida	.8 (1)	2.5 (2)	3.3 (3)	4.2 (3)	.8 (1)	--	3.3 (3)
Cultellus pellucidus	.8 (1)	--	--	2.5 (3)	--	--	1.7 (2)
Mya truncata	--	.8 (1)	.8 (1)	--	1.7 (1)	.8 (1)	.8 (1)
Corbula gibba	2.5 (2)	3.3 (3)	5.0 (4)	.8 (1)	--	3.3 (2)	3.3 (2)
Thracia convexa	.8 (1)	2.5 (2)	2.5 (2)	--	3.3 (3)	3.3 (2)	3.3 (3)
Onoba vitrea	66.7 (5)	53.3 (6)	78.3 (6)	23.3 (5)	30.0 (5)	22.5 (6)	20.8 (6)
Turritella communis	4.2 (2)	4.2 (2)	5.8 (3)	2.5 (2)	--	3.3 (3)	5.8 (4)
Natica alderi	2.5 (2)	.8 (1)	3.3 (4)	.8 (1)	1.7 (2)	.8 (1)	7.5 (5)
Cylichna cilindracea	5.8 (4)	3.3 (2)	9.2 (5)	1.7 (2)	4.2 (4)	10.0 (5)	3.3 (2)
CRUSTACEA							
Processa parva	2.5 (2)	11.7 (5)	12.5 (5)	5.0 (3)	5.8 (3)	2.5 (3)	5.0 (3)
Macropipus holsatus	--	--	--	--	--	.8 (1)	--
Macropipus spec. juv.	--	--	--	--	--	--	.8 (1)
Ebalia cranchii	.8 (1)	--	--	--	--	--	--
Nephrops norvegicus	--	--	--	.8 (1)	--	--	--
Upogebia stellata	--	--	.8 (1)	.8 (1)	--	--	--
Upogebia deltaura	14.2 (5)	5.0 (4)	7.5 (6)	14.2 (4)	11.7 (5)	7.5 (4)	.8 (1)
Upogebia spec. juv.	.8 (1)	--	--	--	--	--	--
Callianassa subterranea	90.8 (6)	55.0 (6)	96.7 (6)	102.5 (6)	92.5 (6)	68.3 (6)	95.8 (6)
Decapoda larven	--	--	--	.8 (1)	--	--	--
Nebalia bipes	--	1.7 (1)	--	--	--	5.8 (3)	--
Gastrosaccus spinifer	--	--	--	--	.8 (1)	--	--
Eudorella truncatula	--	--	--	--	--	--	--
Pseudocuma longicornis	--	--	--	.8 (1)	--	--	--
Diastylis bradyi	22.5 (5)	15.0 (4)	5.0 (4)	1.7 (2)	--	1.7 (2)	4.2 (3)
Ione thoracica	.8 (1)	--	--	2.5 (2)	2.5 (2)	--	5.8 (4)
Pseudione spec.	.8 (1)	1.7 (1)	1.7 (2)	3.3 (1)	--	--	2.5 (2)
Orchomenella nana	.8 (1)	--	--	--	--	--	--
Leucothoe incisa	--	--	--	--	--	.8 (1)	--
Ampelisca brevicornis	1.7 (2)	--	--	--	--	.8 (1)	.8 (1)
Ampelisca tenuicornis	9.2 (6)	16.7 (6)	3.3 (2)	6.7 (4)	12.5 (4)	15.8 (6)	4.2 (2)
Ampelisca spec. juv.	.8 (1)	--	--	--	--	--	--
Cheirocratus sundevalli	--	--	--	--	.8 (1)	--	--
Harpinia antennaria	5.0 (4)	3.3 (3)	2.5 (1)	7.5 (3)	5.0 (3)	15.0 (6)	10.8 (5)
Aora typica	--	--	--	5.0 (2)	--	.8 (1)	--
Photis longicaudata	--	--	--	.8 (1)	--	--	--

Table 12.continued.

Distance to discharge site (m)	25	75	125	200	500	1000	5000
ECHINODERMATA							
Amphiura filiformis	830.0 (6)	611.7 (6)	310.8 (6)	946.7 (6)	411.7 (6)	1745.0 (6)	514.2 (6)
Amphiura chiajei	11.7 (5)	10.0 (4)	3.3 (2)	10.0 (4)	4.2 (4)	13.3 (3)	6.7 (3)
Ophiura texturata	--	.8 (1)	.8 (1)	--	--	--	--
Ophiura albida	--	.8 (1)	--	--	1.7 (2)	.8 (1)	.8 (1)
Echinocardium cordatum	2.5 (1)	4.2 (3)	5.0 (3)	5.8 (3)	3.3 (3)	10.0 (5)	5.8 (5)
Cucumaria elongata	1.7 (2)	--	4.2 (5)	2.5 (2)	.8 (1)	1.7 (1)	.8 (1)
Cucumaria frondosa	2.5 (3)	2.5 (3)	1.7 (1)	5.0 (3)	2.5 (2)	3.3 (3)	3.3 (4)
OTHER TAXA							
Nemertinea	P (5)	P (4)	P (5)	P (6)	P (5)	P (6)	P (5)
Nematoda	--	--	.8 (1)	2.5 (1)	--	--	.8 (1)
Turbellaria	16.7 (5)	12.5 (5)	5.0 (3)	5.0 (3)	3.3 (2)	12.5 (5)	6.7 (5)
Phoroniden	P (6)	P (5)	P (6)	P (5)	P (6)	P (6)	P (6)
Harp. copepoda	--	--	--	--	--	--	.8 (1)
Parasitaire copepoda	--	.8 (1)	--	--	--	--	--
Oligochaeta	2.5 (3)	1.7 (2)	--	--	--	--	--
Holothuroidea	--	--	--	.8 (1)	1.7 (2)	.8 (1)	.8 (1)
Echiurida	2.5 (1)	9.2 (5)	7.5 (3)	3.3 (1)	4.2 (3)	.8 (1)	.8 (1)
Sipunculida	38.3 (6)	19.2 (5)	27.5 (6)	37.5 (5)	48.3 (6)	24.2 (5)	21.7 (6)
Anthozoa	.8 (1)	--	--	--	--	--	--
Ascidiacea	--	--	2.5 (3)	--	--	--	.8 (1)
Foraminiferida	--	.8 (1)	--	--	--	--	--
Tot. nr. of ind. (n.m^{-2})	2035	1620	1268	1928	1348	3390	1487
Nr. of identified species	69	65	74	68	62	62	66

P= present, not counted

Appendix Table 13 . Data location L6-3, residual current transect, survey Oct. 1991.
Number of analysed samples per station: 6.
Number of identified species.
Mean densities ($n.m^{-2}$).
Tot. number of ind. per m^2 per station.
Number of samples ( ) in which species are present.

Distance to discharge site (m)	25	75	125	200	500	1000	5000
POLYCHAETA							
Harmothoe lunulata	.8 (1)	.8 (1)	--	--	.8 (1)	.8 (1)	4.2 (2)
Harmothoe longisetis	.8 (1)	.8 (1)	--	.8 (1)	.8 (1)	--	.8 (1)
Harmothoe spec. juv.	--	.8 (1)	1.7 (1)	--	2.5 (2)	2.5 (3)	2.5 (1)
Gattyana cirrosa	1.7 (2)	3.3 (2)	3.3 (3)	4.2 (4)	--	4.2 (3)	3.3 (2)
Pholoe minuta	101.7 (6)	68.3 (6)	202.5 (6)	189.2 (6)	79.2 (6)	67.5 (6)	103.3 (6)
Sthenelais limicola	--	.8 (1)	1.7 (2)	5.8 (4)	--	2.5 (3)	2.5 (3)
Eteone longa	--	--	1.7 (2)	.8 (1)	.8 (1)	--	--
Eteone spec. juv.	--	--	--	.8 (1)	--	2.5 (3)	2.5 (2)
Mysta barbata	--	.8 (1)	1.7 (2)	--	--	--	--
Anaitides groenlandica	--	--	--	.8 (1)	1.7 (2)	2.5 (3)	4.2 (4)
Anaitides maculata	.8 (1)	--	1.7 (2)	.8 (1)	.8 (1)	--	--
Anaitides spec. juv.	--	1.7 (2)	4.2 (2)	2.5 (3)	3.3 (2)	2.5 (3)	2.5 (1)
Eumida sanguinea	--	--	--	1.7 (2)	--	--	1.7 (2)
Syllis spec.	--	--	--	.8 (1)	--	--	--
Ophiodromus flexuosus	3.3 (3)	4.2 (4)	5.0 (4)	5.0 (5)	10.0 (5)	5.8 (5)	5.8 (5)
Gyptis capensis	9.2 (4)	4.2 (4)	7.5 (4)	6.7 (4)	6.7 (6)	5.8 (4)	4.2 (4)
Exogone hebes	1.7 (2)	2.5 (3)	--	.8 (1)	--	.8 (1)	--
Nereis longissima	4.2 (4)	2.5 (3)	1.7 (2)	4.2 (4)	5.8 (3)	.8 (1)	.8 (1)
Nereis spec. juv.	.8 (1)	5.8 (5)	5.0 (3)	6.7 (5)	5.0 (3)	5.0 (4)	11.7 (6)
Nephtys hombergii	10.0 (4)	9.2 (6)	16.7 (6)	10.8 (6)	10.0 (5)	15.8 (6)	25.0 (6)
Nephtys incisa	--	--	.8 (1)	--	--	--	.8 (1)
Nephtys cirrosa	--	--	--	--	1.7 (2)	--	1.7 (2)
Nephtys spec. juv.	.8 (1)	--	.8 (1)	--	1.7 (1)	.8 (1)	5.8 (3)
Goniada maculata	--	1.7 (1)	12.5 (5)	6.7 (5)	.8 (1)	3.3 (1)	7.5 (5)
Lumbrineris latreilli	38.3 (6)	32.5 (6)	77.5 (6)	54.2 (6)	33.3 (6)	40.0 (6)	24.2 (6)
Lumbrineris fragilis	--	10.8 (1)	--	--	--	--	--
Orbinia sertulata	--	--	--	1.7 (2)	--	.8 (1)	.8 (1)
Poecilochaetus serpens	1.7 (1)	2.5 (2)	3.3 (3)	.8 (1)	11.7 (6)	.8 (1)	.8 (1)
Spio filicornis	2.5 (2)	--	--	--	--	.8 (1)	--
Polydora ciliata	--	2.5 (2)	--	--	--	--	--
Polydora pulchra	5.0 (2)	1.7 (2)	3.3 (4)	1.7 (2)	1.7 (2)	--	.8 (1)
Polydora guillei	11.7 (3)	4.2 (1)	25.8 (6)	16.7 (4)	14.2 (5)	4.2 (2)	--
Spiophanes bombyx	324.2 (6)	683.3 (6)	1940.8 (6)	2390.8 (6)	1491.7 (6)	830.0 (6)	2131.7 (6)
Magelona alleni	--	--	--	--	.8 (1)	--	--
Chaetopterus variopedatus	1.7 (2)	2.5 (2)	--	.8 (1)	2.5 (2)	2.5 (2)	--
Tharyx marioni	--	--	.8 (1)	5.0 (4)	--	1.7 (2)	.8 (1)
Chaetozone setosa	.8 (1)	--	3.3 (3)	2.5 (2)	--	--	8.3 (6)
Diplocirrus glaucus	5.0 (4)	8.3 (4)	8.3 (5)	13.3 (6)	5.8 (3)	6.7 (5)	12.5 (6)
Scalibregma inflatum	--	6.7 (4)	20.0 (6)	14.2 (6)	13.3 (5)	13.3 (6)	2.5 (3)
Ophelina acuminata	--	.8 (1)	.8 (1)	3.3 (3)	.8 (1)	1.7 (2)	1.7 (2)
Capitella capitata	.8 (1)	2.5 (2)	.8 (1)	--	--	--	--
Mediomastus gracilis	40.8 (6)	30.0 (6)	141.7 (6)	158.3 (6)	115.8 (6)	85.0 (6)	7.5 (5)
Notomastus latericeus	4.2 (4)	7.5 (3)	10.0 (6)	15.8 (6)	4.2 (4)	4.2 (3)	65.0 (6)
Owenia fusiformis	4.2 (3)	3.3 (3)	5.0 (6)	9.2 (4)	5.8 (4)	6.7 (3)	.8 (1)
Myriochele oculata	3.3 (2)	1.7 (2)	7.5 (4)	9.2 (6)	5.0 (2)	5.0 (3)	32.5 (6)
Lanice conchilega	20.8 (4)	88.3 (6)	84.2 (6)	154.2 (6)	123.3 (6)	72.5 (6)	187.5 (6)
Polycirrus medusa	--	--	.8 (1)	3.3 (2)	--	--	--
Lagis koreni	49.2 (6)	30.8 (6)	50.8 (6)	125.8 (6)	30.8 (6)	45.8 (6)	118.3 (6)
Pectinaria auricoma	1.7 (1)	2.5 (2)	9.2 (6)	12.5 (6)	4.2 (3)	5.8 (2)	8.3 (4)
Ampharete finmarchica	--	2.5 (2)	.8 (1)	.8 (1)	.8 (1)	5.8 (4)	.8 (1)
Amphicteis gunneri	--	1.7 (1)	.8 (1)	2.5 (2)	3.3 (3)	.8 (1)	4.2 (2)
Eupolymnia nebulosa	--	--	.8 (1)	.8 (1)	--	--	--
Lysilla loveni	--	--	.8 (1)	--	--	--	--

Table 13. continued.

Distance to discharge site (m)	25	75	125	200	500	1000	5000
MOLLUSCA							
Nucula turgida	10.8 (5)	12.5 (5)	63.3 (6)	62.5 (6)	40.0 (6)	55.8 (6)	157.5 (6)
Thyasira flexuosa	.8 (1)	--	3.3 (3)	1.7 (2)	--	.8 (1)	--
Lepton squamosum	2.5 (1)	--	4.2 (4)	.8 (1)	1.7 (2)	--	--
Montacuta ferruginosa	2.5 (1)	6.7 (3)	10.8 (5)	21.7 (6)	7.5 (4)	10.0 (5)	25.8 (5)
Mysella bidentata	387.5 (6)	535.8 (6)	870.8 (6)	829.2 (6)	574.2 (6)	336.7 (6)	770.8 (6)
Arctica islandica	--	.8 (1)	.8 (1)	.8 (1)	--	--	--
Acanthocardia echinata	--	.8 (1)	--	--	--	--	--
Dosinia lupinus	--	--	--	--	.8 (1)	.8 (1)	--
Venus striatula	1.7 (1)	--	5.8 (4)	5.0 (4)	1.7 (2)	2.5 (3)	6.7 (5)
Spisula subtruncata	--	--	--	--	3.3 (2)	10.0 (6)	37.5 (5)
Spisula elliptica	--	--	--	1.7 (2)	2.5 (1)	--	10.8 (1)
Tellina fabula	--	--	--	--	3.3 (1)	9.2 (4)	5.8 (4)
Tellina tenuis	--	.8 (1)	1.7 (1)	--	10.0 (5)	7.5 (3)	.8 (1)
Abra alba	5.0 (4)	8.3 (4)	11.7 (6)	17.5 (6)	16.7 (5)	45.0 (6)	23.3 (6)
Abra nitida	.8 (1)	.8 (1)	--	1.7 (1)	--	--	--
Gari fervensis	--	--	--	.8 (1)	--	--	.8 (1)
Cultellus pellucidus	--	1.7 (1)	--	.8 (1)	.8 (1)	6.7 (4)	.8 (1)
Mya truncata	--	--	.8 (1)	--	.8 (1)	--	--
Corbula gibba	.8 (1)	.8 (1)	.8 (1)	--	--	1.7 (2)	2.5 (3)
Thracia phaseolina	5.8 (3)	4.2 (4)	6.7 (5)	5.8 (3)	9.2 (6)	20.0 (6)	38.3 (6)
Thracia convexa	--	--	.8 (1)	.8 (1)	--	--	--
Thracia spec. juv.	.8 (1)	--	--	--	--	--	--
Onoba vitrea	--	--	--	.8 (1)	--	--	8.3 (4)
Turritella communis	2.5 (3)	1.7 (2)	.8 (1)	.8 (1)	1.7 (2)	.8 (1)	--
Natica alderi	15.8 (6)	3.3 (3)	24.2 (6)	15.0 (6)	24.2 (4)	21.7 (6)	37.5 (6)
Cylichna cilindracea	8.3 (5)	7.5 (4)	19.2 (6)	20.8 (6)	7.5 (5)	9.2 (5)	9.2 (5)
CRUSTACEA							
Processa parva	.8 (1)	4.2 (5)	5.0 (3)	1.7 (2)	10.8 (6)	2.5 (2)	2.5 (2)
Pontophilus spec. juv.	.8 (1)	--	--	--	--	--	--
Pagurus bernhardus	.8 (1)	--	--	--	--	--	--
Corystes cassivelaunus	2.5 (1)	--	7.5 (5)	4.2 (2)	1.7 (1)	3.3 (3)	10.8 (5)
Upogebia deltaura	11.7 (6)	.8 (1)	15.8 (6)	7.5 (6)	5.0 (5)	5.8 (5)	--
Upogebia spec. juv.	--	--	2.5 (2)	--	1.7 (2)	--	1.7 (2)
Callianassa subterranea	85.8 (6)	107.5 (6)	93.3 (6)	94.2 (6)	89.2 (6)	94.2 (6)	44.2 (6)
Decapoda larven	--	--	--	--	--	.8 (1)	.8 (1)
Nebalia bipes	--	1.7 (1)	--	--	--	--	--
Eudorella truncatula	--	.8 (1)	5.0 (3)	1.7 (2)	2.5 (2)	.8 (1)	1.7 (2)
Iphinoe trispinosa	--	--	.8 (1)	--	--	--	--
Diastylis bradyi	14.2 (4)	2.5 (2)	23.3 (6)	9.2 (6)	11.7 (3)	10.8 (5)	32.5 (5)
Ione thoracica	1.7 (1)	5.8 (3)	--	2.5 (2)	4.2 (3)	9.2 (4)	6.7 (4)
Pseudione spec.	.8 (1)	--	--	--	--	--	--
Melita dentata	--	--	--	--	--	--	.8 (1)
Scopelocheirus hopei	--	--	--	--	--	2.5 (1)	.8 (1)
Orchomenella nana	--	--	--	.8 (1)	--	.8 (1)	--
Leucothoe incisa	7.5 (3)	.8 (1)	.8 (1)	2.5 (2)	10.8 (5)	9.2 (5)	30.0 (6)
Metopa alderi	--	--	--	--	.8 (1)	--	--
Ampelisca brevicornis	5.0 (3)	3.3 (3)	8.3 (6)	14.2 (6)	12.5 (5)	9.2 (5)	9.2 (4)
Ampelisca tenuicornis	4.2 (4)	5.8 (3)	15.0 (5)	10.0 (4)	14.2 (6)	8.3 (5)	5.8 (4)
Bathyporeia guilliamsoniana	--	--	.8 (1)	--	.8 (1)	.8 (1)	--
Harpinia antennaria	--	3.3 (3)	16.7 (5)	41.7 (6)	20.8 (6)	27.5 (6)	25.0 (6)
Perioculodes longimanus	--	--	--	--	--	.8 (1)	--
Synchelidium haplocheles	--	--	--	--	--	--	2.5 (2)
Corophium insidiosum	--	--	.8 (1)	1.7 (2)	--	--	--
ECHINODERMATA							
Amphiura filiformis	238.3 (6)	705.8 (6)	1877.5 (6)	1670.8 (6)	840.0 (6)	589.2 (6)	754.2 (6)
Amphiura chiajei	6.7 (2)	62.5 (6)	66.7 (6)	77.5 (6)	60.0 (6)	45.0 (6)	80.8 (6)
Acronida brachiata	--	--	--	--	--	--	.8 (1)

Table 13. continued.

Distance to discharge site (m)	25	75	125	200	500	1000	5000
Ophiura texturata	1.7 (1)	--	--	1.7 (2)	--	3.3 (2)	2.5 (2)
Ophiura albida	1.7 (2)	--	--	.8 (1)	.8 (1)	--	.8 (1)
Ophiura spec. juv.	--	.8 (1)	5.8 (1)	3.3 (2)	5.8 (4)	20.0 (5)	32.5 (5)
Echinocardium cordatum	2.5 (1)	35.0 (5)	121.7 (6)	269.2 (6)	158.3 (6)	145.0 (6)	254.2 (6)
OTHER TAXA							
Nemertinea	P (3)	P (6)	P (6)	P (6)	P (6)	P (6)	P (6)
Nematoda	--	--	6.7 (2)	--	--	.8 (1)	.8 (1)
Amphioxus	--	--	--	--	1.7 (2)	--	--
Turbellaria	5.0 (4)	--	8.3 (4)	6.7 (5)	5.8 (3)	3.3 (2)	5.0 (4)
Phoroniden	P (5)	P (6)	P (6)	P (6)	P (6)	P (6)	P (5)
Oligochaeta	--	12.5 (3)	11.7 (3)	9.2 (3)	3.3 (2)	10.8 (5)	2.5 (2)
Echiurida	--	--	--	--	--	.8 (1)	--
Sipunculida	3.3 (3)	1.7 (2)	6.7 (4)	5.8 (5)	5.0 (4)	5.0 (4)	.8 (1)
Anthozoa	--	.8 (1)	3.3 (3)	--	--	.8 (1)	--
Tot. nr. of ind. ($n.m^{-2}$)	1493	2576	5996	6472	3974	2807	5247
Nr. of identified species	55	61	67	73	65	66	68

P= present, not counted

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