Influence of pollution on the harpacticoid copepods of two North Sea estuaries

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Keywords: copepoda, pollution, estuaries, North Sea

Abstract

Seasonal monitoring of the meiobenthos in the Dutch estuaries revealed an anomaly in density and diversity of harpacticoid copepods in the Westerschelde.

Another Dutch estuary, the Eems Dollard, has comparable hydrodynamical, physical and sedimentological, characteristics and a similar fauna, but even in the severely organically polluted oligohaline mudflats of this estuary, annual average density and diversity of endo-epibenthic harpacticoid communities are higher than at similar less enriched meso- to polyhaline biotopes of the Westerschelde.

Besides the concentrations of inorganic pollutants, such as phosphates and nitrates, the concentrations of pesticides, cyanide, detergents, phenoles, oils, polychlorobenzenes, polycyclic aromatic hydrocarbons and heavy metals were compared in both estuaries and compared to suggested permissive levels when available. From this it appears that these pollutants are present in the Westerschelde either in too low concentrations to be considered dangerous or at concentrations comparable to those occurring in the Eems Dollard, except for heavy metals.

The load of a.o. Zn, Cu and Pb is distinctly and persistently higher in sediments and suspensions of the Westerschelde than in the Eems Dollard and copper is continuously present in a concentration at which, according to bioassays, egg production and larval development of planktonic copepods are severely affected. The remarkable scarcity of harpacticoid life on nutrient rich mudflats of the Westerschelde is thus probably due to heavy metal pollution.

Since no other hardbodied meio- and macrobenthic taxa nor the plankton of this estuary show such a marked impoverishment, benthic harpacticoids prove to be suitable as indicators for the first stages of ecosystem-breakdown in estuarine and coastal zones polluted by trace-metals.

Introduction

The adverse effects of pollution on living resources are an important motive in pollution monitoring but the possibility of looking for these effects in the field has not received appropriate attention (McIntyre & Pearce, 1980). Biological parameters are usually discarded in routine monitoring because their intrinsic variability is considered too large. Much of the research effort in the biological monitoring of pollution is directed towards the individual organism and not to measurements on populations or communities (Bayne, 1979).

However, changes in entire communities due to pollution are probably the only cases likely to seriously arouse public concern. Monitoring communities has the advantage over other methods that it measures these changes directly. In many estuaries and coastal areas an early warning based on subtle changes is no longer needed and a set of measures to evaluate how the situation evolves becomes necessary – even if the causality of the phen-

Hydrobiologia 112, 143-160 (1984).

omena remains unknown.

In this study we looked at assemblages of harpacticoid copepods from two estuaries in the Netherlands. Their possible utility in ecological monitoring has been discussed by Heip (1980), who stressed that they could be excellent 'indicator-organisms', as they live associated with the sediments, which are the ultimate sink of most pollutants, and as they are small and thus more sensitive.

The two estuaries which we will compare are the Westerschelde, the most southern estuary in the Netherlands, and the Eems-Dollard, which is its most northern estuary, on the border with Germany. Although situated in the Netherlands, the Westerschelde carries a huge load of many different kinds of pollutants originating in Belgium and France and is an open sewer right to the Belgian–Dutch border where the influence of marine waters becomes important. The Eems-Dollard, on the other hand, is only occasionally polluted, but then very heavily with organic matter from potato-flour mills, annually in early autumn. Apart from this difference in degree of pollution, both estuaries have many similar characteristics and harbour similar species of harpacticoids. For both estuaries, data concerning water quality have been collected over the years by Rijkswaterstaat in the Netherlands (Ministry of Public Works) and by several groups connected with the Management Unit of the Mathematical Model of the North Sea and the Schelde estuary in Belgium (Ministry of Public Health).

Material and methods

The localisation of the stations is charted in Fig. 1. In the Westerschelde, 21 stations divided over four transects (Vlissingen, Terneuzen, Ossenisse and Valkenisse) were sampled from September 1978 till September 1979 on the following dates: 27–29 Sept. 1978; 11–13 Dec. 1978; 3–5 Apr. 1979 and 3–5 Sept. 1979. Most of the stations are intertidal and situated on shallow sand- or mudflats between + 1.0 and -3.0 MTL. Truly subtidal samples were taken in the channels at depths of -25 to -60 m MLWS on each transect in September 1980. In the same month macro-algae were collected from intertidal pools on sandbanks near the mouth of the estuary (Vlissingen-transect). Meiofauna at the

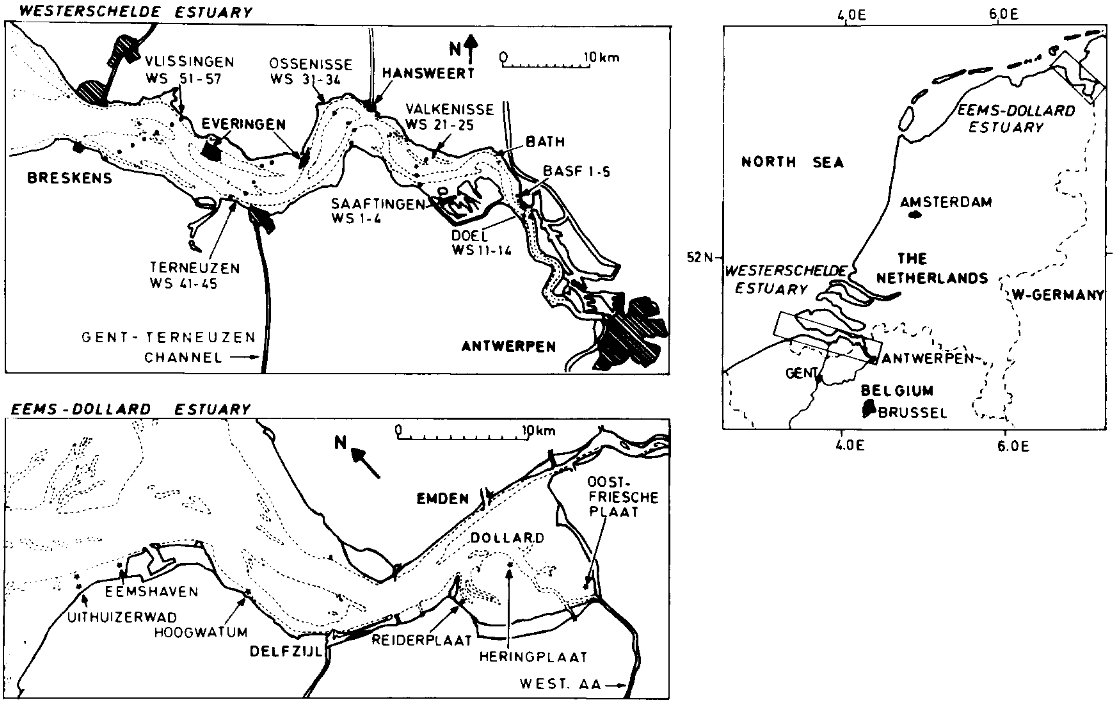

Fig. 1. Localisation of sampling stations.

Doel transect was sampled and studied a year earlier (Holvoet, 1978) from May 1977 till May 1978 over six sampling periods on the following dates: 5 May 1977; 17 Jun. 1977; 1 Sept. 1977; 18 Oct. 1977; 26 Jan. 1978 and 9 May 1978.

The sampling technique differed according to tidal level, but in all cases a core with a 10.2 cm^2 inner surface was used. On deep subtidal stations a modified Reineck box-corer (Farris & Crezee, 1976) was used. From undisturbed samples four core-subsamples were taken. Two replicates for meiofauna studies were fixed with warm formalin (70 °C) to a final concentration of 4%, the two other cores for chemical and sedimentological analysis were frozen immediately. In shallow subtidal water (-3.5 m below the water surface) samples were collected with a 'meiosticker', a telescoping tube (max. length 5.5 m) equiped with a head into which the core is screwed (Govaere & Thielemans, 1979). On the other (intertidal) stations the samples were handcollected with the core.

In the Eems-Dollard estuary benthic harpacticoids were sampled from September 1976 till July 1977 on six transects. The location of these transects is also shown in Fig. 1. At Uithuizerwad, nine stations on a transect of 2400 m were sampled on 21 Sept. 1976 and 1 Feb. 1977. At Eemshaven a 150 m transect (8 stations) and at Hoogwatum a 100 m transect (4 stations) were sampled on 23 Sept. 1976 and 25 Mar. 1977. At the Reidersplaat the 4 stations along a 400 m transect were sampled on 28 Dec. 1976 and 29 Mar. 1977. The Heringplaat-stations (interdistance 150 m) were sampled on 27 Jul. 1977 only and 5 stations on the Oost-Friesche Plaat (interdistance 500 m) were sampled on 15 Sept. 1976 and 16 Nov. 1976. All stations are situated on intertidal sand- or mudflats. All samples were handcollected with a core with a 9.1 cm^2 inner surface except at the Oost-Friesche Plaat where a 4.5 cm^2 inner surface core was used because of the great abundance of meiofauna (nematodes) there.

In the laboratory all samples were processed over 250 μm and 38 μm sieves. For sandy sediments, the meiobenthos was elutriated from both fractions using the trough method (Barnett, 1968; Heip, 1976). For muddy sediments the organisms from the smaller fraction were extracted using a density gradient centrifugation technique (Bowen *et al*, 1972; de Jonge & Bouwman, 1977). After staining with rose Bengal all groups of the meiobenthos were counted, and the harpacticoids were studied systematically.

Biomass was measured using a Mettler ME 22 microbalance, accurate to 0.1 μg. The individual adult dry weight per species was measured after drying the specimen in an oven at 110 °C during 2 hours. Copepodites were assumed to have an eighth of adult weight, as there are five copepodite stages each approximately doubling in weight.

As a measure of species diversity the Brillouin formula was used:

$$H = \frac{1}{N} \log_2 \frac{N!}{N_1!N_2 \ldots N_s!}$$

in which N_1 is the number of individuals of the i-th species and N is the total number of individuals. We used this index because each sample was considered as a finite collection which was fully censused (Pielou, 1975), For samples containing few specimens the value of this index is considerably lower than the value of the more commonly used Shannon-Wiener index but in 'normal' samples the differences is small.

Median grain size of the sand fraction was determined using the IBP-technique (Buchanan & Kain, 1971). 25 g of oven-dried sediment was analysed. Classification is according to the Wentworth scale. Stations with a mud-fraction (silt-clay particles smaller than 62 μm) lower than 2% are considered here as 'pure sand stations', whereas stations with a mud content in excess of 2% are termed 'muddy sand stations'. The amount of organic matter was estimated by loss of weight on ignition at 550 °C (Wollast, 1976). The amount of organic carbon was determined using the method of El Wakeel & Riley (1956).

The annual mean salinity of each transect was used to classify the transects in the salinity zones defined by the Venice system (Remane & Schlieper, 1971). Chemical analysis of the water column and determination of trace metals in water and sediments of the Verdronken Land van Saaftinge was done by Dr. M. Vaes at the 'Provinciaal Instituut voor Milieuhygiëne, Oost Vlaanderen'. For heavy metals X-ray fluorescence and atomic adsorption spectrophotometry was used, for detergents the methylene blue method.

Table 1. Main hydrodynamical and physical characteristics of the Westerschelde and Eems-Dollard estuaries.

	Westerschelde	Ref.	Eems-Dollard	Ref.
Type of estuary	coastal plain estuary with slight partial stratification and vertical mixing	(1)	Idem	(5)
Average flood volume	1300 10^6 m^3	(2)	410 10^6 m^3	(5)
Average freshwater volume	89 m^3 sec^{-1}	(3)	83 m^3 sec^{-1}	(5)
Range of normal tidal current velocity	0.7–1.5 $msec^{-1}$	(4)	1.0–1.5 $msec^{-1}$	(5)
Vertical tidal amplitude	4–5 m	(3)	2–3 m	(5)
Tidal wave	semilunar M_2, 12h25 min	(3)	Idem	(5)
Length of sea arm	80 km	(3)	33 km*	(5)
Width at landlocked mouth	5 km	(2)	9 km	(6)
Channel depth at low tide	av: 10–18 m max. 63 m		av: 4–8 m max. 16 m	

*This is the length of the landlocked sea arm part of the estuary.
Ref.: (1) Peters, 1975; (2) Theuns, 1975; (3) Peters & Sterling, 1976; (4) Wollast & Peters, 1978; (5) Dorrestein, 1960; (6) Dorrestein & Otto, 1960.

Characteristics of the two estuaries

The main hydrodynamical and physical characteristics of the two estuaries are summarized in Table 1. Differences in these factors and topography (the Westerschelde is elongated and narrow, the Eems-Dollard truncated and broad) are correlated with the distance of the respective estuaries to the bottle-neck of the English Channel (Van Veen, 1950). Tidal volumes and tidal amplitudes are higher in the Westerschelde and hence turbulence is higher, which is still more pronounced because the Western Scheldt is open to the prevailing winds and not protected by an island chain as the Eems-Dollard.

Lateral extensions, traces of former inundations, occur in both estuaries: the Verdronken Land van Saaftinge (Drowned Land of Saaftinge) is a high saltmarsh (27 km^2) with a *Spartina* and *Puccinellia*-dominated vegetation, crisscrossed by an intricate system of tidal creeks connected with the Westerschelde. In the Eems-Dollard estuary, the Dollard is a vast intertidal mudflat (100 km^2), interlaced with creeks. Vegetation is confined to the edges.

In the Westerschelde, pure sands with a median grain size around 200 μm and a mud content never in excess of 2% are found on the sandflats situated near the tidal channels, where tidal currents and wave turbulence are strongest. The sediment is well oxygenated up to the maximum depth sampled (20 cm) and is displaced in a sawteeth-movement around the banks (Peters & Sterling, 1976). The organic matter content averages between 1.5 and 2.5% and the organic carbon content is around 0.05% (Table 2). Pure sands occur also in the Eems-Dollard in areas with similar hydrodynamical conditions, but the mean grain size here is smaller (110 to 125 μm) and the organic carbon content higher (0.1–0.3%).

Muddy sands occur over the whole Westerschelde estuary, along the edges, where currents

Table 2. Average values of median grainsize (Md μm), mud percentage (fraction < 63 μm) and percentage organic matter (O.M.) and organic carbon (O.C.) at each station group, divided in 'pure sand' stations (% mud < 2% over the whole sampling period) and 'muddy sand' stations (% mud > 2% during the whole sampling period).

Station		Md μm	%Mud	%O.M.	%O.C.
Westerschelde estuary					
Doel	ms (8)	190	9.1	5.2	–
Valkenisse	ps (2)	183	8.5	1.2	0.04
	ms (3)	147	8.8	7.7	1.62
Ossenisse	ps (3)	215	0.4	1.4	0.06
	ms (1)	155	2.9	4.4	0.29
Terneuzen	ps (3)	210	0.5	2.4	0.05
	ms (2)	143	5.2	5.4	0.34
Vlissingen	ps (2)	230	0.7	2.7	0.05
	ms(5)	164	12.9	6.3	0.37
Saaftinge	ms (4)	104	16.2	1.3	0.18
Eems-Dollard estuary					
Oost-Friesche Plaat	ms (5)	132	12.7	–	2.74
Heringplaat	ps (5)	122	1.7	–	0.26
Reiderplaat	ms (4)	86	14.4	–	1.03
Hoogwatum	ms (4)	93	6.2	–	0.87
Eemshaven	ps (8)	114	1.1	–	0.11
Uithuizerwad	ms (9)	112	4.7	–	–

and wave velocity are minimal, allowing fine particles to settle. The grain size is on average around 150 μm and the mud percentage is well above 3% throughout the year. Stations with very soft sediments (black muds) occur at Doel (WS 14: av. 53% mud) and at the Vlissingen transect (WS 51: av. 21% mud). The organic matter content of muddy sands in the Westerschelde is around 5 to 7% and organic carbon averages between 0.3 and 1.6%, except at Doel where it is higher. At this transect all stations, even in turbulent water, contain more than 3% mud during at least part of the year due to their localisation in the flocculation zone (see further) (Table 2). The top 5 cm of the sediments of the Saaftinge salt marsh also consist of black muds and the sands below are anoxic.

The muddy sands of the Eems-Dollard have a mud content of 4 to 14% and an organic carbon content of 0.8 to 2.7%.

Transport and accumulation of pollutants

The Westerschelde estuary. About 1.52×10^6 tons of suspended solids are discharged into the estuary annually by the Schelde river, highly polluted by organic compounds (20,600 t N a^{-1}, 125,000 t P a^{-1}, 250,000 t org. mat. a^{-1}) and heavy metals (2000 t Zn a^{-1}, 495 t Cu a^{-1}, 450 t Pb a^{-1} and 1.52 t Hg a^{-1}). In a zone with a salinity between $1^0/_{00}$ and $5^0/_{00}$ located between Anterpen and Doel most of the suspended matter flocculates and is sedimented. The seaward limit of this flocculation zone may go as far as Hansweert during periodes of increased river discharge (Peters, 1975). About 1.2 10^6 t a^{-1} of solids of continental origin are trapped in this area together with 0,8 10^6t a^{-1} of solids, mainly coarser clastics, of marine origin. Most of the heavy metal load is coprecipitated and fixed in the sediments as insoluble sulphides (Wollast, 1976; Wollast & Peters, 1978). The amounts of these pollutants in the sediments and in the suspended matter are therefore considerable (Table 3). As a result of the activity of heterotrophic bacteria the waters in the flocculation zone are frequently anoxic, especially in summer, and toxics such as H_2S and ammonia are released (Billen *et al,* 1976). Nitrogen and phosphorus compounds are also precipitated but relatively large amounts still persist in the seaward part of the estuary (Hansweert–Vlissingen) and even at the mouth ammonia is still present (Table 4).

Table 3. Trace metal concentrations in sediment and suspended matter (1) Hoenig (1976) (heavy metal concentration in sediment expressed in mg kg^{-1} dwt of total sample); (2) Vaes (pers. commun.) (idem); (3) Salomons & Mook (1977) (heavy metals in sediment expressed in mg kg^{-1} of a representative sediment containing 50% particles < 16 μm); (4) Data communicated by Ir. J. A. W. de Wit, Rijkswaterstaat RIZA, Lelystad, The Netherlands.

	Zn mg kg^{-1}	Cu mg kg^{-1}	Pb mg kg^{-1}	n
Westerschelde (1)				
Flocculation zone				
(Antwerpen-Hansweert)	476	91	138	14
Sediment	476	91	138	14
Suspension	1090	215	277	5
Seawards zone	209			
(Hansweert-Vlissingen)	209			
Sediment	209	58	101	12
Suspension	260	107	130	5
Gent-Terneuzen Channel (1)				
Suspension	3314	157	928	2
Saaftinge Saltmarsh (2)				
Sediment	121	0	41	1
Eems-Dollard				
Dollard				
Sediment (3)	150	24	47	18
Suspension (4)	230	27	57	19
Outer Eems				
(Uithuizerwad-Eemshaven)				
Sediment (3)	153	11	45	18
Suspension (4)	160	25	47	19

About 2.2 10^5t a^{-1} of solids of continental origin are deposited in the seaward part of the estuary. The concentration of heavy metals in the suspended matter decreases as they dissolve or become desorbed, e.g. dissolved Cu increases from about 10 $\mu g\ l^{-1}$ at Doel to 20 $\mu g\ l^{-1}$ at Vlissingen, dissolved Pb increases from 7 $\mu g\ l^{-1}$ at Antwerpen to 40 $\mu g\ l^{-1}$ at Doel, then decreases again to 20 $\mu g\ l^{-1}$ at Vlissingen (Wollast, 1976). This increases may be due to the degradation of the organic matter precipitated in the flocculation zone; on the other hand, iron and magnesium precipitate in the seaward zone as hydrous oxides (Wollast & Peters, 1978), and as they are known scavengers of heavy metals in this form (Duinker & Nolthing, 1976, 1977) this could explain the still very high concentrations of heavy metals found in the sediments of the seaward zone Hansweert–Vlissingen. Hoenig (1978) discovered a small but important accumulation area of heavy metals in front of the harbour of Terneuzen. The

Table 4. Annual averages (from fortnightly samples) of salinity, oxygen, ammonia, total phosphates and total organic carbon in surface waters of the Westerschelde estuary (RIZA, 1978–1979) and Eems-Dollard estuary (RIZA, 1976–1977). Total organic carbon averages for the second estuary were calculated from data from Laane (1980). The Saaftinge saltmarsh samples were collected in July 1980.

	Sal $^0/_{00}$	O_2 mg l^{-1}	$NH_4 \cdot N$ mgN l^{-1}	$PO_4 \cdot$ mgP l^{-1}	OC mg C l^{-1}
Westerschelde 1978–1979					
Doel	9.1 0.9–14.8	1.9 0.7–7.5	3.46 1.64–5.96	1.19 0.71–2.35	14.89 11.2–27.8
Valkenisse	15.6 6.1–21.0	6.4 4.4–7.6	1.69 0.45–3.28	0.78 0.45–1.35	10.6 5.1–19.8
Ossenisse	20.6 9.9–27.1	8.0 5.6–9.2	0.93 0.05–2.78	0.61 0.38–1.11	9.8 6.7–18.8
Terneuzen	25.3 18.7–28.6	8.6 6.8–9.7	0.53 0.03–1.39	0.43 0.22–0.81	8.7 5.4–15.4
Vlissingen	30.2 24.3–32.0	9.0 5.9–11.3	0.30 0.03–0.94	0.21 0.09–0.43	9.1 4.6–9.9
Saaftinge 1980	18.2	6.3	1.60	0.32	–
Eems-Dollard 1976–1977					
Oost-Friesche Plaat	7.7 0.18–15.8	7.3 0.0–11.4	1.55 0.07–11.0	0.70 0.16–3.33	–
Hering + Reiderplaat	13.0 3.9–21.9	8.7 5.8–11.8	1.00 0.03–2.03	0.38 0.13–0.60	10.7 7.6–20.0
Hoogwatum	20.7 15.4–26.6	9.0 6.0–11.2	0.50 0.03–1.06	0.25 0.11–0.46	5.6 3.3–9.4
Uithuizerwad + Heemshaven	30.2 28.0–32.0	9.5 8.0–11.1	0.19 0.01–0.46	0.19 0.05–0.37	4.4 2.3–5.4

solid matter deposited in this area (only 2 10^4 t a^{-1}) originates from the Gent-Terneuzen channel which has an extremely high concentration of heavy metals in the particulate fraction of its waters (Table 3).

Apart from heavy metals many other toxic compounds are monitored in the Westerschelde. Pesticides and PCB's occur over the whole estuary in extremely low concentrations and only lindane is sporadically found in the water column. Fluoride is found in a concentration of about 1.5 mg l^{-1} which is 2–3 times higher than in all other Dutch waters. The concentration of phenol at the mouth is only sporadically in excess of 1 μg l^{-1}. In this region oil concentrations are around 0.1 μg l^{-1} with a maximum of 1.2 μg l^{-1} and at Doel polynuclear aromatic hydrocarbons were present in concentrations of 0.3–0.7 μg l^{-1}. Synthetic anionactive detergents are continuously present in concentrations of 0.04–0.05 mg mannotol OT l^{-1} over the whole estuary. Cyanide is practically never detectable.

In September 1980 a water and sediment sample was taken at the mouth of the main creek draining the Verdronken Land van Saaftinge. Nutrient concentrations in the water column are low (Table 4) and comparable to concentrations found at the mouth of the Westerschelde. The concentrations of heavy metals, especially copper, in the sediments are low when compared to the Westerschelde. The main reason for this is probably the limited exchange between the tidal watermass that moves in and out of the creeks and the Westerschelde main waters (De Pauw, 1975).

The Eems-Dollard estuary. The load of suspended solids carried by the river Eems is estimated at 65,000 t a^{-1} (Hinrich, 1974), The turbidity maximum is limited to a narrow area between Distum and Emden (Postma, 1960). All the particulate matter originating from the river is transported by the tidal currents to the eastern (German) part of the Dollard where it settles. Freshwater is also carried into the Dollard by the Westerwoldse Aa river. This river is organically polluted by potato flour mills. The input of organic matter varies from 1 200 ton in summer to 25 000 ton in late autumn, making up for about 0.5 –10 × 10^3 C a^{-1} (Schröder *et al,* 1976). Concentrations on nutrients and organic matter

Table 5. Mean annual density N (ind. 10 cm^{-1}) biomass B (μg dwt. 10 cm^{-2}) and diversity H (bits $ind.^{-1}$) of benthic harpacticoids of the Westerschelde estuary, Saaftinge saltmarsh and Eems-Dollard estuary, per stationgroup and according to sediment composition (ms = muddy sand; ps = pure sand) at each stationgroup. (st = number of stations; n = number of samples).

Station group	Type	St	n	N	B	H
Westerschelde						
Doel	ms	8	64	0.10 ± 0.05	0.23 ± 0.10	0.008 ± 0.008
Valkenisse	ps	2	10	0.90 ± 0.71	0.17 ± 0.17	0
	ms	3	13	0.77 ± 0.54	2.34 ± 2.21	0.04 ± 0.04
	x̄			0.83 ± 0.42	1.40 ± 1.25	0.02 ± 0.02
Ossenisse	ps	3	15	12.0 ± 8.54	3.17 ± 2.21	0.11 ± 0.07
	ms	1	5	9.6 ± 7.31	15.34 ± 15.10	0.16 ± 0.16
	x̄			10.85 ± 6.58	6.21 ± 3.97	0.12 ± 0.07
Terneuzen	ps	3	15	0.64 ± 0.29	1.66 ± 0.80	0
	ms	2	10	2.30 ± 1.10	3.87 ± 1.81	0.24 ± 0.13
	x̄			1.33 ± 0.52	2.58 ± 0.89	0.10 ± 0.06
Vlissingen	ps	2	10	26.40 ± 10.84	6.67 ± 2.84	1.08 ± 0.21
	ms	5	25	10.36 ± 3.25	20.17 ± 6.81	0.37 ± 0.09
	x̄			14.94 ± 3.97	16.66 ± 5.13	0.57 ± 0.10
Saltmarsh Saaftinge	ms	4	7	69.71 ± 24.68	236.16 ± 83.51	1.14 ± 0.09
Eems-Dollard estuary						
Oost-Friesche Plaat	ms	5	22	17.38 ± 4.15	29.23 ± 7.09	0.41 ± 0.09
Heringplaat	ps	4	4	36.07 ± 21.57	33.56 ± 21.75	0.93 ± 0.20
Reiderplaat	ms	4	17	44.57 ± 6.37	55.99 ± 9.41	1.44 ± 0.11
Hoogwatum	ms	3	7	46.10 ± 20.03	72.30 ± 32.84	1.42 ± 0.13
Eemshaven	ps	5	17	87.79 ± 7.55	147.95 ± 13.12	2.20 ± 0.07
Uithuizerwad	ms	9	14	89.98 ± 34.52	127.60 ± 45.85	1.47 ± 0.20

reach maxima in the south-eastern part of the Dollard (Oost-Friesche plaat), where annual averages of oxygen, nutrients and organic matter are similar to the values occurring near the seaward limit of the flocculation zone in the Western Scheldt (Table 4). During the peak activity of the potato flour mills, maximum concentrations are even above the ones occurring at Doel. During autumn the water becomes anoxic and high amounts of H_2S and ammonia are found (Bouwman & Kop, 1979). The concentrations of oxygen and nutrients in the rest of the Eems-Dollard are similar to the ones occurring in the seaward part of the Western Scheldt.

The concentrations of heavy metals are very low when compared to the Westerschelde, both in the sediments and in the suspended matter (Table 3). The difference is even larger than indicated in Table 3 but comparison is difficult because Salomons & Mook (1977) and Essink (1980) use different units. The Eems-Dollard received several tons of mercury annually from 1960 till 1975. The concentration of dissolved mercury dropped from 0.31 $\mu g\ l^{-1}$ in 1975 to 0.10 $\mu g\ l^{-1}$ in 1978, while the mercury content of particulate matter averaged 1.76 $\mu g\ l^{-1}$ (Essink, 1980). Similar values are cited for the Western Scheldt (RIZA, 1978, 1979).

Concentrations of the pesticides aldrin, telodrin, dieldrin, endrin and DDE in muscle tissue of *Mytilus* at Delfzijl are at least 2–3 times higher in the Eems-Dollard than at the mouth of the Westerschelde (Koeman, 1971). Hexachlorobenzene was usually below the detection limit (0.01 $\mu g\ l^{-1}$) in surface waters and with concentrations of 0.05–0.99 mg kg^{-1} wwt in *Crangon* (Fonds & Greve, 1979) i.e. about 2–3 higher than at the mouth of the Western Scheldt (Hagel & Tuinstra, 1974). Concentrations of PCB's are similar in Eems-Dollard shrimps (0.05 –0.14 mg kg^{-1}wwt.) and at the mouth of the Westerschelde (0.07–0.18 mg kg^{-1} wwt.) (Ten Berge & Hillebrand, 1974; Essink, 1976). The maximum amount of anionactive detergents measured in the Eems river was 0.3 mg l^{-1}.

The Harpacticoid fauna

A total of 23 species of harpacticoids was found on the intertidal flats of the Westerschelde (Table 6). They can be divided in two distinct assemblages:

Table 6. Species list of benthic harpacticoids of the Westerschelde estuary and Saaftinge saltmarsh, according to the salinity zones (E.P. = Eu-polyhaline; P. M. = poly-mesohaline; M = mesohaline, M.O. = meso-oligohaline). Individual biomass B_i (in μg dwt) per species, mean density N (ind. 10 cm^{-2}); dominance in % and absolute frequency (st = number of stations; n = number of samples).

Westerschelde estuary	B_i	E.P. (st=12; n=69)			P.M. (st= 4; n=20)			M (st= 5; n=23)			M.O. (st= 9; n=63)		
		N	%	f	N	%	f	N	%	f	N	%	f
Canuella perplexa T&A Scott	3.90	0.06	0.6	3	–	–	–	–	–	–	–	–	–
Halectinosoma sarsi Boeck	8.40	0.05	0.5	3	–	–	–	–	–	–	–	–	–
Pseudobradya beduina Monard	1.50	0.10	1.0	6	–	–	–	–	–	–	–	–	–
Pseudobradya minor (T&A Scott)	1.50	0.06	0.6	2	0.05	0.4	1	–	–	–	–	–	–
Arenosetella germanica Kunz	0.63	0.01	0.1	1	–	–	–	–	–	–	–	–	–
Arenosetella tenuissima (Klie)	0.63	–	–	–	0.2	1.7	1	0.04	5.5	1	–	–	–
Eurterpina acutifrons (Dana)	1.80	0.06	0.6	2	–	–	–	–	–	–	–	–	–
Tachidius discipes Giesbrecht	1.90	1.74	18.7	8	1.5	13.2	1	–	–	–	–	–	–
Harpacticus flexus Brady	1.80	0.01	0.1	1	–	–	–	–	–	–	–	–	–
Harpacticus littoralis Sars	1.80	0.03	0.3	1	–	–	–	–	–	–	–	–	–
Stenhelia palustris Brady	3.19	0.88	9.4	12	0.25	2.2	2	0.59	50.0	1	0.06	57.1	4
Amphiascoides debilis (Giesbrecht)	0.80	0.25	2.6	4	0.10	0.8	2	–	–	–	–	–	–
Nitocra typica Boeck	0.20	–	–	–	–	–	–	–	–	–	0.01	14.2	1
Paramesochra sp. A sensu Mielke	0.20	1.15	12.3	6	–	–	–	–	–	–	–	–	–
Kliopsyllus constrictus (Nicholls)	0.20	1.28	13.7	7	0.50	4.4	3	–	–	–	–	–	–
Evansula pygmaea (T. Scott)	0.25	0.40	4.3	7	0.05	0.4	1	–	–	–	–	–	–
Leptastacus laticaudatusNicholls	0.23	0.01	0.1	1	–	–	–	–	–	–	–	–	–
Paraleptastacus espinulatus sensu Moore	0.25	1.50	16.1	9	8.0	70.7	4	0.30	38.8	1	–	–	–
Arenocaris bifida Nicholls	0.23	0.06	0.6	3	–	–	–	–	–	–	–	–	–
Huntemannia sp.	2.80	0.01	0.1	1	–	–	–	–	–	–	–	–	–
Paronychocamptus curticaudatus (Boeck)	2.60	0.40	4.3	3	0.05	0.4	1	–	–	–	–	–	–
Asellopsis intermedia (T. Scott)	1.00	1.22	13.1	11	0.10	0.8	1	0.04	5.5	1	0.03	28.5	1
Plathychelipus littoralis (Brady)	3.56	0.01	0.1	1	–	–	–	–	–	–	–	–	–
Number of individuals 10 cm^{-2}		9.29			10.80			0.79			0.10		
Total number of species		21			10			4			3		
Salt marsh of Saaftinge st = 4 n = 7													
Alteutha depressa Baird	8.00							0.14	0.2	1			
Stenhelia palustris Brady	3.19							13.42	19.2	7			
Nannopus palustris Brady	3.40							44.42	63.7	7			
Paronychocamptus nanus (Sars)	0.60							0.14	0.2	1			
Plathychelipus littoralis (Brady)	3.56							11.57	16.5	7			
Number of individuals 10 cm^{-2}								69.69					
Total number of species								5					

a mesobenthic assemblage, consisting of small, interstitially living grazers, and an endo-epibenthic assemblage consisting of large burrowing or epibenthic detritus-feeders. Characteristic species are *Paramesochra* sp. A, *Kliopsyllus constrictus* and *Paraleptastacus espinulatus* for the mesobenthic assemblage and *Canuella perplexa, Pseudobradya spp.* and *Tachidius discipes* for the endo-epibenthic assemblage. These two distinct assemblages never co-occur in the Westerschelde because the two distinct habitat types are incompatible: in the pure, coarser sands the absence of detritus or epibenthic diatoms and the high turbulence exclude the presence of epibenthic copepods. In the low energy zone the interstitial habitat is unavailable because of the fine texture of the sands (< 200 μm) and a mud content in excess of the limit of 2–3% (Govaere *et al*, 1980).

The occurrence of a relatively well developed interstitial assemblage is restricted to two very tur-

bulent stations at the mouth (Vlissingen transect). Here a total of 7 species was found with dominant forms *Paraleptastacus espinulatus* (33.8%), *Kliopsyllus constrictus* (29.2%) and *Paramesochra* sp. A (26.5%). In the eu-polyhaline zone at Terneuzen only one interstitial species was found, *Evansula pygmaea* (3 specimens), although the sediment is suitable for interstitial life at 3 stations (15 samples). In the poly-mesohaline zone 3 interstitial species were found, with *P. espinulatus* extremely dominant (93%). In the mesohaline zone (Valkenisse) only a few specimens of *P. espinulatus* were found, while at Doel the interstitial habitat is absent (Table 6).

Mean annual diversity, density and biomass all follow the same trend: highest values are found at the mouth, there is a decrease to very low levels at Terneuzen, an increase again at Ossenisse and another decrease to zero at Doel (Fig. 2; Table 5). The maximum average values found at the Vlissingen transect are H = 1.08 bits ind.$^{-1}$ N=26.4 ind. 10 cm^{-2} and B = 6.6μg dwt 10 cm^{-2}. Maximum values were H = 1.64 bits ind. (Vlissingen transect in autumn), N = 128 ind. 10 cm^{-1} (Vlissingen transect) and B = 33 μg dwt 10 cm^{-1} (Ossenisse transect). Diversity was zero in 80% of the pure sand stations.

The most diverse endo-epibenthic assemblage again occurs in stations of the Vlissingen transect at the mouth of the estuary with a total of 13 species, decreasing to 8 at Terneuzen, 7 at Ossenisse and 3 at Valkenisse and Doel. In the muddy sand stations *Tachidius discipes* is dominant in eu-polyhaline (35%) and poly-mesohaline zones (66%) whereas *Stenhelia palustris* is dominant in the meso- (81%) and meso-oligohaline zones where *T. discipes* is absent (Table 6). *T. discipes, S. palustris* and *Asellopsis intermedia* represent 80–90% of the whole endoepibenthic fauna in all salinity zones.

Mean annual diversity (Table 5) decreases gradually from the mouth (H = 0.37 bits ind.$^{-1}$ to Doel (H = 0.01 bits ind.$^{-1}$, but density and biomass show the same low values at the Terneuzen transect as the interstitial species, with higher values at Ossenisse as well. Maximal diversity noted was 1.24 bits ind.$^{-1}$ (Vlissingen transect in winter), maximum density was 68 ind. 10 cm^{-2} (Vlissingen transect) and maximum biomass 147 μg dwt 10 cm^{-2}. Diversity was zero in 84% of all muddy sand stations.

In the Saaftinge salt-marsh a total of only five species was recorded with *Nannopus palustris* dominant (63.7%). The Saaftinge epibenthic assemblage is totally different from the Westerschelde estuary in species composition since, except for *Stenhelia palustris,* the other species do not occur or are rare in the estuary. Mean annual diversity was 1.14 (max H = 1.39 in summer and min H = 0.81 in winter) (Table 5; Fig. 2).

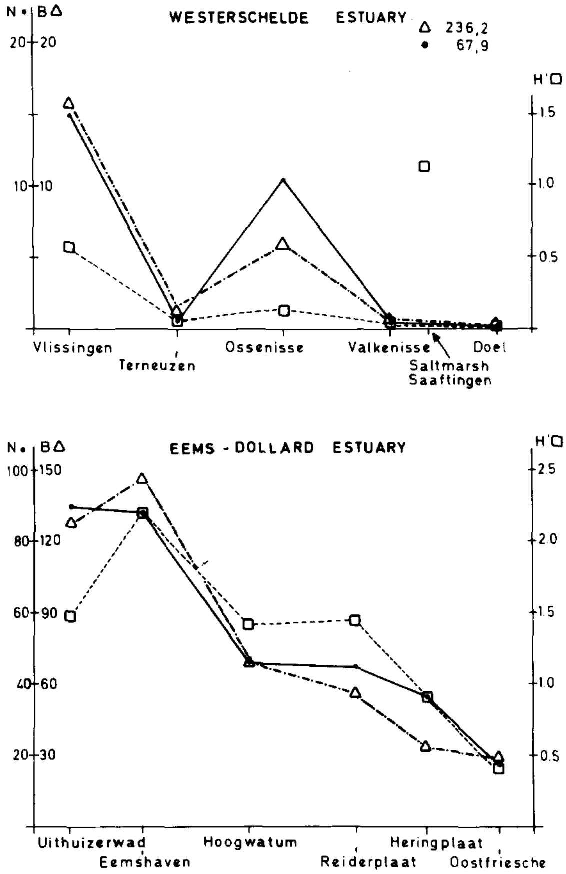

Fig. 2. Longitudinal profile of average annual density N (ind. 10 cm^{-2}) average annual biomass B (μg dwt 10 cm^{-2}) and average annual diversity H (bits ind.$^{-1}$; Brillouin index) of the epibenthic harpacticoids in the Westerschelde and Eems-Dollard estuaries (see also Table 5).

In the Eems-Dollard estuary a total of 24 species was recorded (Table 7). They all belong to the endoepibenthic assemblage and are found in the pure as well as in the muddy sands. Their presence in pure sands is probably made possible by the large amounts of benthic diatoms which cover the surface of the sediment as a film during low tide, and which can persist because wave velocity is lower here than in the Western Scheldt. An interstitial

Table 7. Species list of benthic harpactacoids of the Eems-Dollard estuary, subdivided according to the salinity zones. For explication of abbreviations see Table 6.

Eems Dollard estuary	B_i	E.P. (st=17;n=31)			P.M. (st= 6;n= 7)			M (st=11;n=21)			M.O. (st= 9;n=22)		
		N	%	f	N	%	f	N	%	f	N	%	f
Canuella perplexa T & A Scott	3.9	6.9	7.8	27	1.10	2.4	3	–	–	–	–	–	–
Halectinosoma curticorne Boeck	0.8	–	–	–	–	–	–	16.5	42.2	20	0.2	1.4	2
Halectinosoma herdmani T & A Scott	2.2	7.8	10.3	26	0.62	1.4	3	–	–	–	–	–	–
Halectinosoma gothiceps Giebrecht	1.0	–	–	–	0.62	1.4	4	–	–	–	–	–	–
Halectinosoma elongatum Sars	1.0	0.03	0.05	1	1.88	4.2	1	–	–	–	–	–	–
Pseudobradya minor (Boeck)	1.0	14.9	18.1	22	5.61	13.0	5	0.79	2.0	5	–	–	–
Pseudobradya beduina Monard	1.0	0.21	0.3	2	0.47	1.0	4	0.05	0.1	1	–	–	–
Ectinosomatidae sp. indet	1.0	0.21	0.3	2	–	–	–	0.15	0.4	1	–	–	–
Arenosetella tenuissima (Klie)	0.2	1.0	1.1	11	–	–	–	–	–	–	–	–	–
Euterpina acutifrons (Dana)	1.8	0.07	0.1	1	–	–	–	–	–	–	–	–	–
Tachidius discipes Giesbrecht	1.9	11.9	15.1	18	5.34	11.8	4	3.77	8.6	14	0.20	1.2	2
Microarthridion littorale (Poppe)	1.6	2.3	3.1	5	26.11	57.4	4	4.55	10.7	16	0.30	1.7	2
Thompsonula hyaenae (Thompson)	2.0	1.7	2.3	3	0.47	1.0	3	–	–	–	–	–	–
Harpacticus flexus Brady	1.8	12.9	16.2	24	1.57	3.5	3	–	–	–	–	–	–
Stenhelia palustris Brady	1.5	1.0	1.2	11	–	–	–	2.51	5.7	10	8.54	49.1	16
Amphiascoides debilis (Giesbrecht)	0.8	–	–	–	0.31	0.7	1	0.41	1.0	4	–	–	–
Ameira parvula (Claus)	0.7	0.07	0.1	1	0.15	0.3	1	–	–	–	–	–	–
Enhydrosoma propinquum (Brady)	0.7	2.87	3.7	10	0.15	0.3	1	–	–	–	–	–	–
Enhydrosoma longifurcatum (Sars)	0.7	0.10	0.1	1	–	–	–	–	–	–	–	–	–
Nannopus palustris Brady	2.1	0.03	0.05	1	–	–	–	4.72	10.7	10	6.93	39.9	11
Paronychocamptus curticaudatus (Boeck)	2.6	4.86	6.2	21	0.47	1.0	3	–	–	–	–	–	–
Paronychocamptus nanus (Sars)	0.6	–	–	–	0.31	0.7	2	7.44	16.9	20	1.0	0.0	2
Asellopsis intermedia (T. Scott)	1.0	12.25	12.3	28	0.94	2.1	4	–	–	–	–	–	–
Plathychelipus littoralis Brady	2.1	0.42	0.5	3	0.31	0.7	2	0.57	1.3	9	–	–	–
Number of individuals 10 cm^{-2}		81.25	100.0		45.54	100.0		43.93	100.0		17.37	100.0	
Total number of species		21			17			11			6		

harpacticoid fauna is absent due to the small grain size (< 200 μm).

In the eu-polyhaline zone (Uithuizerwad, Eemshaven) a total of 21 species was recorded with a dominance of *Harpacticus flexus* (16.2%), *Asellopsis intermedia* (12.3%), *T. discipes* (15.1%) and *Pseudobradya minor* (18.1%). In the mesohaline zone (Reidersplaat, Heringplaat) at the mouth of the Dollard itself, the number of species decreases to 11 with dominance of *Halectinosoma curticorne* (42.2%), *Paronychocamptus nanus* (16.9%) and *M. littorale* (10.7%). In the meso-oligohaline zone (Oost-Friesche plaat) in the organically polluted south-eastern corner of the Dollard, the total number of species is reduced to 6 and only 2 species, *Stenhelia palustris* (49.1%) and *Nannopus palustris* (39.9%) are still relatively abundant. Both are typical for intertidal black muds (Lang, 1948; Noodt, 1957) and *Nannopus palustris* can survive prolonged periods (96 h) in anoxic conditions (Coull *et al*, 1979). However, during the period of maximal sewage output of the potatoflour mills, only *Stenhelia palustris* survived.

Highest annual average diversities occur at the mouth of the estuary with H = 2.20 in pure sands (Eemshaven) and H = 1.47 in muddy sands (Uithuizerwad). Diversity does not decrease significantly upstream since values of H = 1.42 (Hoogwatum) and H = 1.44 (Reidersplaat) were recorded. The low diversity found at Heringplaat, H = 0.93, also situated at the mouth of the Dollard, is based on only one sampling date. The lowest annual average was noted at the Oost-Friesche Plaat H = 0.41 (Table 5; Fig. 2). Maximum value found was H = 2.68 in March at Eemshaven. Diversity was zero in 7% of all samples, which corresponds to 22% of the Oost-Friesche Plaat samples and one of the Uithuizerwad samples (with a low density).

Discussion

In both estuaries, mean annual density and biomass decline inland from the station group closest to the mouth (Fig. 2). While in the Eems-Dollard this decrease is gradual, this is not true in the Westerschelde where an inverse peak occurs at the Terneuzen station group. Whereas there is some resemblance in pattern between the two estuaries, absolute values of all community parameters are completely different. The highest annual averages of density and biomass in the Westerschelde are even lower than the lowest annual averages occurring at the Oost-Friesche Plaat group in the Eems-Dollard (Fig. 2). On the other hand, density recorded in the Saaftinge saltmarsh approaches the highest ones found in the Eems-Dollard estuary, while the biomass recorded in this saltmarsh exceeds all values recorded from this latter estuary.

Summer averages recorded in the adjoining estuaries Oosterschelde and Grevelingen are about 4–7 times higher than the peak summer densities (23 ind. 10 cm^{-2}) noted in the Westerschelde. Surkyn (1977) found averages of 119 ind. 10 cm^{-2} on intertidal mudflats of the Oosterschelde ($n = 7$) and 200 ind. 10 cm^{-2} on permanently flooded mudflats in Lake Grevelingen ($n = 7$).

Literature values are also substantially higher, both for organically polluted and for unpolluted environments. Arlt (1975) records densities of 88 ind. 10 cm^{-2} in front of a sewage outlet on a small town, 165 ind. 10 cm^{-2} 30 meters further off and 96 ind. 10 cm^{-2} at an unpolluted station on muddy sand and sandy sediments of the oligohaline Greifs Walder Bodden. Warwick *et al* (1979) record an average of 279 ind. 10 cm^{-2} on an intertidal mudflat in the Lynher estuary and Coull *et al* (1979) and Fleeger (1980) give a range of average monthly densities of resp. 73–262 ind. 10 cm^{-2} and 75–620 ind. cm^{-2} for S. Carolina salt marshes. In a long term study (9 years; 205 samples) Heip (1980) found a harpacticoid density of on average 211 ind. 10 cm^{-2} in a shallow brackish-water pond.

Although Westerschelde and Eems-Dollard are closely related in species composition, the qualitative parameters reflect an impoverishment of the fauna in the former. There is an overwhelming dominance of the species *Asellopsis intermedia, Tachidius discipes* and *Stenhelia palustris* along the salinity gradient in the Westerschelde, but dominance shifts to different combinations of species in the Eems-Dollard at each station group, and the above-mentioned species are unimportant, except at the Oost-Friesche Plaat. Also interesting is the presence of *Microarthridion littorale* in all intertidal station groups of the Eems-Dollard and its confinement to the eu-polyhaline sublittoral in the Westerschelde, although it is extremely plastic physiologically (Coull *et al,* 1979). *M. littorale* is dominant and often the only species occurring in the polluted subtidal muds in front of the Belgian coast (Van Damme & Heip, 1977; Govaere *et al,* 1980).

In summer samples of an intertidal mudflat of the Oosterschelde an average diversity of $H = 1.8$ was recorded; dominant were *Asellopsis intermedia* (37.4%), *Harpacticus flexus* (36.1%) and *Arenosetella tenuissima* (15%). In a subtidal mudflat in the Grevelingen the average diversity was $H = 1.9$ and the dominant species were *Canuella spp. (C. furcigera* SARS – *C. perplexa:* 56.3%), *Ameira parvula* (CLAUS) (20.8%) and *Harpacticus flexus* (7.1%) (Surkyn 1977).

Fleeger (1980) records monthly mean averages of $H = 1.44$–1.69 for two subtidal stations and $H = 1.50$ for an intertidal site at North Inlet, South Carolina. The highest annual average diversity for the epibenthic community recorded at the Westerschelde ($H = 0.59$) is beneath the lowest average found at the Dollard and is about 3–4 times lower than that of the saltmarsh of Saaftinge and adjacent estuaries or than the montly averages recorded by Fleeger (1980). Heip (1980) recorded in his long-term study a mean annual diversity of $H = 1.06$.

The low average values of all parameters in the Westerschelde are due to a complete absence of Harpacticoids in most samples (65%). When they occur, their density and diversity are low, and the average number of species per sample is usually low as well ($H = 0$ in 80% of all samples). This impoverishment is not confined to the intertidal flats since epiphytic and subtidal epibenthic populations are also present in small numbers and confined to the seaward part of the estuary.

The longitudinal profile of annual average standing stock of the planktonic copepods shows characteristics similar to those observed for the parameters studied here (De Pauw, 1975). The most typical species, *Eurytemora affinis* POPPE, is most abundant in the area of the Saaftinge saltmarsh. The percentage of egg carrying females and nauplii is

highest here, while the relative number of males increases with increasing distance from this area. De Pauw (1975) considers the area in and around the saltmarsh as a distribution and reproduction centre.

Compared to the epibenthic isocommunities occurring in other estuarine systems and in the Eems-Dollard estuary, the poverty of the Westerschelde fauna is striking. While a large number of abiotic factors are similar in both estuaries (Tables 1, 2, 4), there exist three basic differences (i): The Westerschelde estuary is more turbulent, (ii) the amount of solids of continental origin that is sedimented is much higher and (iii) water and sediments are more polluted. One of these factors, or a combination, is hence the cause of a scarcity of harpacticoids in this estuary.

1. The possible influence of turbulence, dredge spoil dumping and increasing load of fine grained solids

The Eems-Dollard and the saltmarsh of Saaftinge are protected from extreme physical conditions, while the Westerschelde is not. Giere (1968) and De Pauw (1975) consider high turbulence, and stream-velocity as more important for the production of the planktonic fauna than the nutrient supply. However, turbulence in the Westerschelde is beneficial to diversification of meiobenthic fauna, since areas of coarse-grained sands, where interstitial life can develop, are maintained on the sandflats between the tidal channels. Moreover, at the mouth where turbulence and stream velocities are highest (sometimes removing the layer of sand during storms) a well-developed interstitial fauna exists. Thus, high turbulence alone can not be the limiting factor at the mouth.

Upstream, however, the areas of coarse grained sands are confined and can be considered as islands. The continuous dumping of dredge spoil and the increasing amounts of solids brought in by the Schelde could hence affect the interstitial fauna drastically by filling up the interstitial spaces periodically.

As interstitial copepods have no free-swimming larvae, recolonization of the 'islands' would be difficult. This could theoretically explain the near-absence of interstitial fauna in such areas as the sandflats at the Terneuzen station group. However, clogging was not observed during our campaigns and the sand remained very pure. Further, clogging cannot explain the poverty of the epibenthos of intertidal mudflats in low energy zones where continuous sedimentation of finer clastics is a normal process and where occasional physical disturbances have no or little effect on the meiofauna (Sherman & Coull, 1980).

2. The possible influence of high amounts of organic matter and nutrients.

The drastic decrease in the copepod fauna at the Oost-Friesche Plaat (Eems-Dollard) during late autumn coincides with the maximum outpout of organic material from the potato flour mills. Organic pollution can hence be considered detrimental at the concentrations recorded.

Since at the Doel transect extreme conditions persist almost throughout the year, this type of pollution can explain the poverty of the benthic copepod fauna found here. Conversely, at the remaining station-groups of the Westerschelde the nutrient load and oxygen depletion are much lower than at the Oost-Friesche Plaat and the poverty of the epibenthic populations on the mudflats, especially in the seaward part of the Westerschelde estuary, can not be explained by this type of pollution here.

3. The possible influence of heavy metal pollution

Concentrations of heavy metals in sediments, particulate matter, and water, of the Westerschelde are higher than in the Eems-Dollard and in the salt marsh of Saaftinge. Very high concentrations occur in the flocculation zone and in front of the harbour of Terneuzen, where an inverse peak occurs in all parameters. The absence of interstitial life in pure sands at the Terneuzen station group may be due to a periodical sedimentation mixing of small amounts (not enough to fill up the interstitial pores) of particulate matter from the Gent-Terneuzen channel with its extreme high load of heavy metals. Breakdown of organic matter in the sediment forms organo-metallic complexes which increase significantly the amounts of heavy metals in the interstitial waters of the oxigenized layer (Bryan, 1976).

Little is known about the effect of heavy metal pollution on copepods. They may take up trace metals, concentrated in detritus, diatoms and bac-

teria, via the digestive tract or in solution via the body surface (absorption) Pérès, 1976), Adsorption of heavy metals to the exoskeleton of copepods (a.o. *Euterpina acutifrons*) has also been demonstrated (Martin, 1970).

Bioassays on the effects of heavy metals on copepods are scarce and mainly limited to epiphytic and planktonic forms. Corner & Sparrow (1956) determined the lethal concentration of a number of mercury and copper compounds, generally considered the most toxic elements together with silver (Bryan, 1971), for *Acartia clausi* GIESBRECHT and Hoppenheid & Sperling (1977) determined the lethal concentration of cadmium for *Tisbe holothuriae* HUME. Reeve *et al* (1976) cite 24 h L.C. 50-values for 3 $\mu g\ l^{-1}$ of mercury for nauplii of *Acartia tonsa* DANA. These lethal concentrations are an order of magnitude above these found in the Westerschelde. However, drastic sublethal effects, especially on feeding and egg production, have been observed at concentrations lower or similar to those occurring in the Westerschelde. Reeve *et al* (1976) found a downward trend in these activities for *Acartia tonsa* at concentrations of 10 to 20 $\mu g\ l^{-1}$ Cu and almost no egg production at 50 $\mu g\ l^{-1}$ Cu (24 h L.C. 50 for *A. tonsa* was 104–311 $\mu g\ l^{-1}$ Cu). For *Calanus plumchrus* MARUKAWA Reeve *et al* (1977) found a 6-fold reduction of egg production at 5 μg Cu l^{-1} and no production at all at 10 μg Cu l^{-1} (24 h L.C. 50 for *C. plumchrus* was 2778 $\mu g\ l^{-1}$).

The only bioassay on a benthic harpacticoid shows similar results: growth and larval development of *Tigriopus japonicus* MORI are inhibited at concentrations of 6.4 $\mu g\ l^{-1}$ Cu in association with 4.4 $\mu g\ l^{-1}$ Cd (d'Agostino & Finney, 1974).

The mean annual concentration of dissolved copper in the Westerschelde lies around 10 $\mu g\ l^{-1}$ at Doel, increasing to 20 $\mu g\ l^{-1}$ towards the sea (Wollast, 1976). Concentrations of dissolved mercury are similar in the Westerschelde (RIZA, 1978–1979) and in the Eems-Dollard (Essink, 1980) (0.50–0.01 μg Hg l^{-1}), but as Corner & Sparrow (1956) found that copper increases the permeability of *Acartia clausi* to mercury poisons, the toxicity of mercury compounds may be different in the two estuaries.

4. Possible influence of chronic oil pollution.

According to Mironov (1969) a concentration of 0.001 ml l^{-1} of crude oil is sufficient to shorten the life span of *Acartia clausi* while Ustach (1979) found that the water-soluble fraction of 200 μl Louisiana crude oil per liter seawater and 1/2 and 3/4 dilutions thereoff halved egg production in *Nitrocra affinis* GURNEY. Ott *et al* (1978) found a significant reduction of broodsize, life span and number of naupli of *Eurytemora affinis* after chronic exposure to naphtalene and methylated derivates at concentrations of about 10 $\mu g\ l^{-1}$. At the seaward part of the Westerschelde the concentration of unsoluble oil (which is, however, not toxic) in the surface waters was around 1.0 $\mu g\ g^{-1}$ in fall and winter, and below the detectable level in spring and summer during our survey (RIZA, 1978–1979). The concentrations of polycyclic aromatic hydrocarbons at Doel are at least one order of magnitude below the values cited by Ott *et al* (1978). In the seaward part of the estuary their concentration is still lower. No major oil spill occurred in the Westerschelde in the years previous to our investigation.

5. Possible influence of other toxicants.

Of the remaining toxicants, only anionactive synthetic detergents and fluoride are continually present in the Westerschelde. Anionactive detergents, the only ones still in use in Belgium and the Netherlands, are the least toxic, but according to Bellan (1976), all tensioactive substances are dangerous, even at low concentrations. Arnoux & Bellan-Santini (1972) found alterations in composition of a mediterranean *Cystoseira stricta* community starting at concentrations of 20 to 50 μg manoxol OT l^{-1}.

While the concentration of detergents in the Westerschelde could affect qualitative aspects of the communities, it is unlikely that it would alter quantitative parameters, since all concentrations for which short-term effects are cited are of the order of 1–100 mg l^{-1}, while for chronic exposure effects a concentration of 0.1 mg l^{-1} seems necessary (Duursma & Marchand, 1974). Using 2 and 4 mg l^{-1} of domestic detergent and 0.8 mg l^{-1} LAS, Fava & Crotti (1979) found that the mean number of nauplii of the copepod *Tisbe holothuriae* either decreased or increased according to the number of adults present. No increase of mortality in the adults was noted. However, an earlier study (Fava & Dalla Venezia, 1976) showed a 30% increase in cumulative mortality after 6 days at 4 mg l^{-1} It must

also be pointed out that detergents are present in the saltmarsh of Saaftinge in similar concentrations as in the Westerschelde and that Arlt (1975) found high densities of harpacticoids in front of an urban sewage outlet.

Fluoride is considered a pollutant because marine organisms can store it in large quantities (Pérès, 1976; Perkins, 1976) and it is hazardous to man. There exists no literature on toxic concentrations for marine organisms.

Other pollutants are only intermittently present in the Westerschelde. Pesticides are either absent or occur in very low concentrations (lindane: 0.01 $\mu g\ l^{-1}$) and conform to the permissive level suggested by Perkins (1976).

Sporadically, concentrations of 1.0 to 5.0 $\mu g\ l^{-1}$ of phenoles occur at the mouth of the Westerschelde. Welch (1980) recommends an allowable maximum concentration of 0.1 mg l^{-1} freshwater and aberrant behaviour in marine organisms (molluscs) is only noted above 10 mg l^{-1} (Perkins, 1976).

6. *Possible influence of other biota*

Small diatoms, an important food source for epibenthic copepods, were counted from three Westerschelde and two Saaftinge samples. They were present in similar quantities and food in the form of diatoms or organic matter may be excluded as a limiting factor. Meiobenthic predators such as *Protohydra* do not occur in the Westerschelde but are abundant in the saltmarsh. There exist, however, important populations of the shrimp *Crangon* and of predatory polychaetes in the estuary (Vermeulen, 1980).

Conclusions

Average annual density and diversity of the benthic harpacticoids in the Westerschelde estuary, when compared to those of similar estuaries, are abnormally low. This is due to the fact that in most winter, spring and autumn samples no harpacticoids are found, with the exception of some stations situated at the estuary mouth (Vlissingen station group). Most impoverished are intertidal, organically enriched, muddy stations, especially before the harbour of Terneuzen, and in the flocculation zone where the parameters studied tend to decline towards zero.

The comparison with the Eems Dollard excludes hydrodynamical, physical and sedimentological characteristics, and even heavy organic enrichment, as possible causes for the near-absence of harpacticoid life over vast stretches of the Westerschelde.

Through elimination, a correlation between anorganic pollution and near-extinction of harpacticoid communities seems to be an inevitable conclusion. Since the Westerschelde contains a vast array of such pollutants, and since synergistic and antagonistic effects of such chemicals exist, it is impossible to indicate with absolute certainty the pollutant or group of pollutants that affects the harpacticoids in particular.

However, when comparing data from the Eems Dollard, from the Verdronken Land van Saaftinge and from the Westerschelde, it is clear that the Westerschelde differs from the other two estuarine ecosystems in its higher load of heavy metals in solution, in suspension, and in the sediments. That these pollutants are the main cause of the scarcity of benthic harpacticoids is corroborated by bioassays on (planktonic) copepods which indicate that at least copper is present the whole year through in concentrations more than sufficient to severely affect egg production and larval development.

In comparison with the harpacticoids, the other taxa in the Westerschelde show considerably less or practically no stress (except in the highly polluted oligohaline flocculation zone): nematodes are well represented throughout the Westerschelde, with annual average densities in excess of 1000 ind. cm^{-2}; only at 3 stations in the flocculation zone do diversity and density occasionally reach zero (Van Damme *et al,* 1980). The macrobenthic fauna shows a similar resistance to pollution: a diversity study of the estuaries of the Schelde-Rhine delta by Wolff (1973), a decade ago, showed no significant difference of this parameter in the Westerschelde when compared to the other estuaries, and a recent follow-up study in this estuary (Vermeulen, 1980) indicated that the macrofauna had not deteriorated since then. Only locally are abnormally low values found. This is the case for the flocculation zone, where diversity declines toward zero, but such a phenomenon is observed in other less polluted estuaries as well (Wolff, 1973). Macrobenthos is also scarce at 3 stations of the Terneuzen group, but these lie close to the main navigation channel, and

the scarcity was hence considered to be the result of physical disturbances such as dredging and wave actions by ships (Vermeulen, 1980).

The plankton also shows a decline in density in front of Terneuzen harbour and in the flocculation zone, but this decrease is relatively small and densities remain at 'normal' levels compared to other estuaries, probably because stocks are regularly renewed by the currents (De Pauw, 1975; Bakker & De Pauw, 1975).

Other meiobenthic taxa, such as hydrozoans, turbellarians, gastrotrichs, tardigrades, ostracodes, apparently occur throughout the estuary except in the flocculation zone, but rarely in high densities. *Protohydra leuckarti* GREEFF, e.g., was only found in two samples (Van Damme *et al*, 1980). Since we do not possess comparative data from other Dutch estuaries and since it is difficult to obtain reliable counts of soft-bodied organisms from fixed samples, little can be concluded from these low densities. No other estuarine taxon seems thus so clearly affected than the benthic harpacticoids.

A similar sensitivity of harpacticoids was observed by Govaere *et al* (1981) in the polluted Belgian coastal waters, where diversity of this group is negatively affected over a much vaster area than all other meio- and macrobenthic taxa studied.

Due to their sensitivity to pollution, which seems specific to heavy metals, benthic harpacticoids appear to be a most useful indicator of this type of pollution in the field and in experimental conditions. This sensitivity has ecological consequences for their predators, littoral and estuarine fish species and shrimps, and especially the younger stages of these.

Importantly, harpacticoids could be used as ecological early warning indicators. They are easily identified as a group, even by technicians, and determination to the species level is not necessary. The number of samples needed to evaluate annual averages of community parameters such as density and biomass is small. A routine procedure involving sampling of harpacticoids is thus simple and cheap.

Acknowledgments

This study was made possible through a grant from the Belgian Ministry of Scientific Policy (Concerted Actions Oceanography); with the help of Rijkswaterstaat, The Netherlands. The second author acknowledges a grant from the Belgian Fund for Scientific Research. For Rijkswaterstaat we want to express our gratitude to Ir. C. Bakker and Ir. J. Gossé. We also thank the crews of the R. V. Welsinge and the R. V. Wijtvliet for their assistance in the Westerschelde. The Eems-Dollard samples were taken with the help of Ir. L. Bouwman from the BOEDE working group.

We thank A. Braeckman, M. De Keere, W. Gijselinck, A. Van Bost and D. Van Gansbeke for technical help, Dr. G. Billen, D. Claeys, Dr. N. De Pauw, Ir. J. A. W. De Wit, Dr. K. Essink, M. Holvoet, Ir. H. Koopmans, Dr. M. Vaes and Prof. R. Wollast for discussion and information and C. Lostrie for typing several manuscripts.

Finally, we want to express our gratitude to M. Vaeremans, who pioneered in the study of the Eems-Dollard harpacticoids and R. Herman who was responsible for the sampling on the Westerschelde and kindly and altruistically assisted with the practical aspects of this work.

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Received 6 July 1983; in revised form 28 September 1983; accepted 30 September 1983.