Limnol. Oceanogr., 40(4), 1995, 766–778

Wind- and tide-induced resuspension of sediment and microphytobenthos from tidal flats in the Ems estuary

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Abstract

The resuspension of microphytobenthos (mainly benthic diatoms) and mud (<55-μm fraction) from tidal flats was studied in the Ems estuary (Netherlands/Germany), of which ~50% is covered by intertidal areas.

Mud and microphytobenthos are resuspended simultaneously from the tidal flats in the estuary. The concentrations of these parameters in the main channels of the estuary are strongly affected by erosion due to wind-induced waves and by settlement during calm weather conditions. The resuspension of mud can be described as a linear function of the "effective windspeed," which is defined as the windspeed averaged over three high-water (6 h bracketing high water) periods preceding sampling. The resuspended fraction of microphytobenthos from the top 0.5-cm layer of sediment can also be described as a linear function of the effective windspeed.

Our data indicate that for this estuary, the proper quantification of resuspension of mud and microphytobenthos requires consideration of relatively large areas.

In estuaries, the phytoplankton usually contains significant numbers of benthic species. Expressed per total volume per reach in the Ems estuary, there can be as many benthic diatoms in the water column of the channels as there are diatom cells in the top 0.5 cm of the total surface of tidal flats (de Jonge 1985). Also, most benthic diatoms live adhering to aggregates of clay minerals and organic matter, some of which form coatings on sand grains (Meadows and Anderson 1968; de Jonge 1985). The adherence of benthic diatoms to coatings indicates the close interaction between these algae and the mud. The species composition in the water column strongly resembles that on the tidal flats (de Jonge 1985). This resemblance suggests a high turnover of sediment as well as of benthic algae between the tidal flats and channels in the estuary.

Because of land reclamation in the Netherlands, the resuspension of sediment from tidal flats has been frequently studied (Kamps 1962), but resuspension of microphytobenthos from tidal flats has seldom been studied in the field. Gabrielson and Lukatelich (1985) showed that chlorophyll *a* increase in the water column was related to resuspension. Especially in shallow systems in which phytoplankton biomass is relatively small or in systems in which phytoplankton is almost absent during winter, resuspended microphytobenthos may form an important additional food source for grazers in the water column and on the tidal flats (Roman and Tenore 1978; Baillie and Welsh 1980; de Jonge 1985; Demers et al. 1987; de Jonge and van Beusekom 1992).

It is well known that turbulent tidal currents play a role in sediment resuspension. Experimental work has shown that this also holds for the resuspension of microphytobenthos (de Jonge and van den Bergs 1987). Our study mainly focuses on the effect of the energy from wind-induced waves which resuspend both fine sediment (mud) and microphytobenthos. The study was started because there were indications that the resuspension dynamics in the estuary may be wind dominated. Our objective was to investigate the possible role of tidal flat systems as a source and sink for suspended matter on the short term and to determine the amounts of suspended mud and suspended microphytobenthos as a function of windspeed in two different regions of the Ems estuary.

Materials and methods

Study area—The Ems estuary borders the Netherlands and Germany (Fig. 1A) and is ~100 km long including its outer delta. The average discharge of the River Ems is 115 $m^3 s^{-1}$. The tidal prism in the inlet between the barrier islands of Rottumeroog and Borkum is ~10^9 m^3. Mean tidal range increases from 2.3 m near the island of Borkum to 3.2 m at Emden and is accompanied by a steep salinity gradient (de Jonge 1991). Strong tidal cur-

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Acknowledgments

We are indebted to the crew of the RV *Ephyra* and to L. A. Villerius and J. van den Bergs for their help and enthusiasm during our many cruises. D. Dijkhuizen is acknowledged for carrying out some statistical analyses. K. Essink and M. Elliott are acknowledged for their comments and an anonymous reviewer for constructive suggestions.

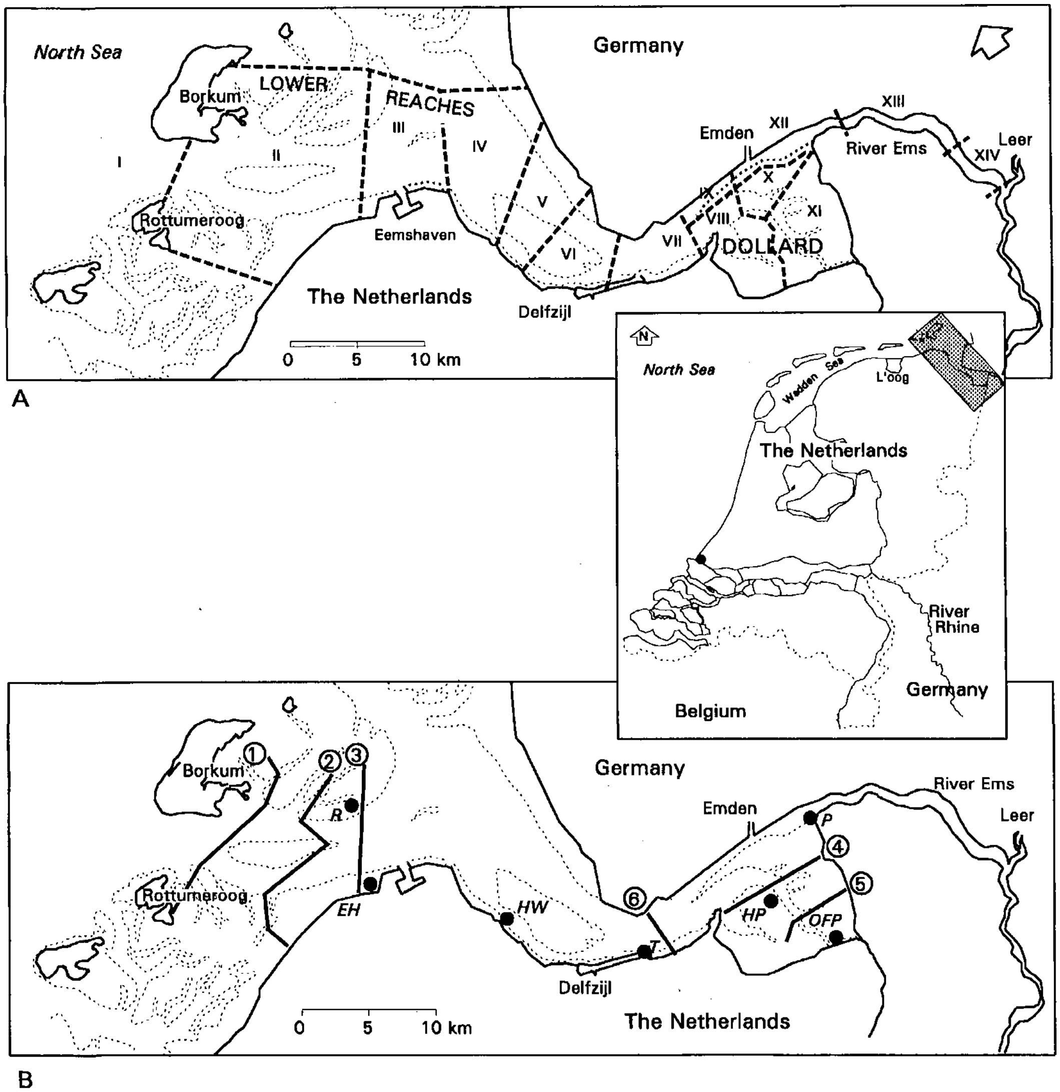

Fig. 1. Map of the Ems estuary. A. The boundaries of the 14 sampling sectors (I–XIV). B. The cross sections (1–6) and stations on the tidal flats: R—Randzel; EH—Eemshaven; HW—Hoogwatum; T—Termunten; HP—Heringsplaat; OFP—Oost Friesche Plaat; P—Pogum. Dotted lines indicate mean low-water level.

rents result in a strong dispersion of water and solutes (Helder and Ruardij 1982). There is a suspended matter gradient, from ~20 g m^{-3} near the tidal inlet between the barrier islands Rottumeroog and Borkum to >400 g m^{-3} in the most turbid part of the estuary between Emden and Leer (de Jonge 1988). This steep gradient is maintained by local accumulation processes in which tidal asymmetry and density circulation play a crucial role (Postma 1967).

To sample the estuary adequately, we divided it into 14 sectors (Fig. 1A). The area of the tidal flats in the lower reaches (sectors II, III, IV and tidal flat stations R, EH, and HW) is 121 × 10^6 m^2 and in the Dollard (sectors VII, VIII, X, XI and tidal flat stations T, HP, and P) is 78 × 10^6 m^2. The water volume in the lower reaches at midtide is 1,030 × 10^6 m^3, and in the Dollard it is 168 × 10^6 m^3.

Expressed per total estuary area, the mean annual primary production of phytoplankton in the estuary is ~200 g C m^{-2} per area (Colijn 1983) and that of microphytobenthos is ~55 g C m^{-2} per area (Colijn and de Jonge 1984). The annual mean biomass of the microphytobenthos in the top 0.5 cm of sediment varies from 26 to 247 mg Chl *a* m^{-2} of tidal flat, or 1.3 to 10.2 g C m^{-2} (de Jonge and Colijn 1994).

Field measurements—Table 1 presents the type and number of measurements that were carried out in the estuary. Winter and spring were chosen as the main sampling periods to minimize the contribution of phytoplankton to the total Chl *a* content in the water column. We did not measure Chl *a* during all the surveys because the original expectation was that the resuspension of benthic diatoms in this estuary could only be quantified by quan-

Table 1. Listing of all cruises in this study. Cross sections shown in Fig. 1B; drogue tracks shown in Fig. 3.

Longitudinal surveys		Cross-sectional surveys			Drogue experiments	
Cruise		Cruise		Cross section	Cruise	
1	4–6 Feb 1980	12	2–4 Dec 1980*	3	23	21 May 1980
2	17–19 Mar 1980	13	2–4 Dec 1980*	6	24	21 May 1980
3	15–16 Apr 1980†	14	17 Mar 1981	1	25	21 May 1980
4	2–4 Dec 1980	15	17 Mar 1981	3	26	16 Jun 1980
5	16–17 Mar 1981	16	25 Mar 1981	4	27	17 Jun 1980
6	18 Mar 1981	17	25 Mar 1981	5	28	18 Jun 1980
7	19 Mar 1981	18	26 Mar 1981	1	29	18 Jun 1980
8	23 Mar 1981	19	26 Mar 1981	3	30	19 Jun 1980
9	25 Mar 1981	20	24 Jun 1981	2	31	9 Sep 1980
10	26 Mar 1981	21	26 Jun 1981	4		
11	24–26 Jun 1981†	22	26 Jun 1981	5		

* Main channel only.
† Rich in phytoplankton.

tifying the resuspension of their substrate—the mud. Field observations showed that this assumption was not correct and that Chl *a* measurements were required.

Cross-sectional surveys were carried out during high tide and under varying weather conditions to determine the concentration of suspended matter (*see Fig. 1B and Table 1*). Above the tidal flats, the water samples (one per sampling station) were taken by hand. Sampling depths were 0.3 m over the flats vs. 2 m in the channels. Samples were collected from distinct stations within the cross section. Two subsamples were sieved and passed through a weighed and dried glass-fiber filter (Whatman GF/C), washed with 10 ml of distilled water, wrapped in aluminum foil, and immediately stored at −20°C for use in determining suspended matter.

Drogue experiments were carried out in May, June, and September 1980 to investigate the tidal excursion of the water mass and the fluctuations in Chl *a* and suspended matter contents in a given water mass during a full tidal cycle. A series of drogues with different lengths was used. Only 5–7 cm of the drogues were above the water surface. Visibility was increased by use of phosphorescent red paint. The drogues had a diameter of 5 cm and a length that covered ~75% of the water depth, such that the tracks mostly represented the tidal and residual water currents and wind drifting of the drogue was probably insignificant. Drogue positions were done by compass bearings and radar distances. The observations started at high tide and then every 30 or 60 min, depending on the movement of the drogue. Water samples were taken by hand from a depth of 0.3 m. Within 2 h, the water samples were sieved and treated as described above. The subsamples were used to determine suspended matter and Chl *a*. The mean current velocity was calculated from the distance the drogue traveled between adjacent positions.

In 1980–1981, the estuary was sampled 11 times during high tide to determine the longitudinal distribution of Chl *a* and suspended matter in the main channels (Table 1). Water was continuously pumped (at 0.3 m^3 min^{-1}) from 2-m depth during passage through each sector. The inflowing volume was divided into several fractions. Water from the smallest tube (50 ml s^{-1}) was sieved through 55-μm plankton gauze and collected, yielding an integrated subsample of ~25 liters per sector. After mixing, a single subsample of 250–1,000 ml (depending on turbidity) was treated as above to determine suspended matter and Chl *a*.

At seven stations, the sediment was sampled to determine the Chl *a* distribution of the microphytobenthos during the longitudinal surveys (Fig. 1B). At each station, 20–25 samples of 2.4-cm diameter each were taken with Perspex tubes and rubber stoppers or a modified ball-stoppered corer. Onboard ship, the upper 0.5 cm of each core was retained. The samples were pooled and mixed thoroughly, after which five subsamples of 1 ml each were taken and stored separately at −20°C until further analysis.

Analyses—The water and sediment samples were lyophilized prior to analysis of suspended matter content and Chl *a*. Chl *a* (mg m^{-3}) was measured spectrophotometrically at 664 nm by the method of Lorenzen (1967) modified according to Moed and Hallegraeff (1978). This modification is the addition of 0.2 ml of 0.4 M HCl, resulting in a better controlled degradation of Chl *a* to pheophytin than in the original method. Suspended matter content was determined gravimetrically (g m^{-3}) after drying for 1 h at 105°C.

Hourly measurements of wind from the coastal station Lauwersoog (L'oog in Fig. 1) were obtained from the Royal Dutch Meteorological Institute (KNMI). Mean windspeed was calculated for each 6-h interval bracketing high tide.

Because of the presumption of nonnormality, Spearman's rank correlation coefficients were used to deter-

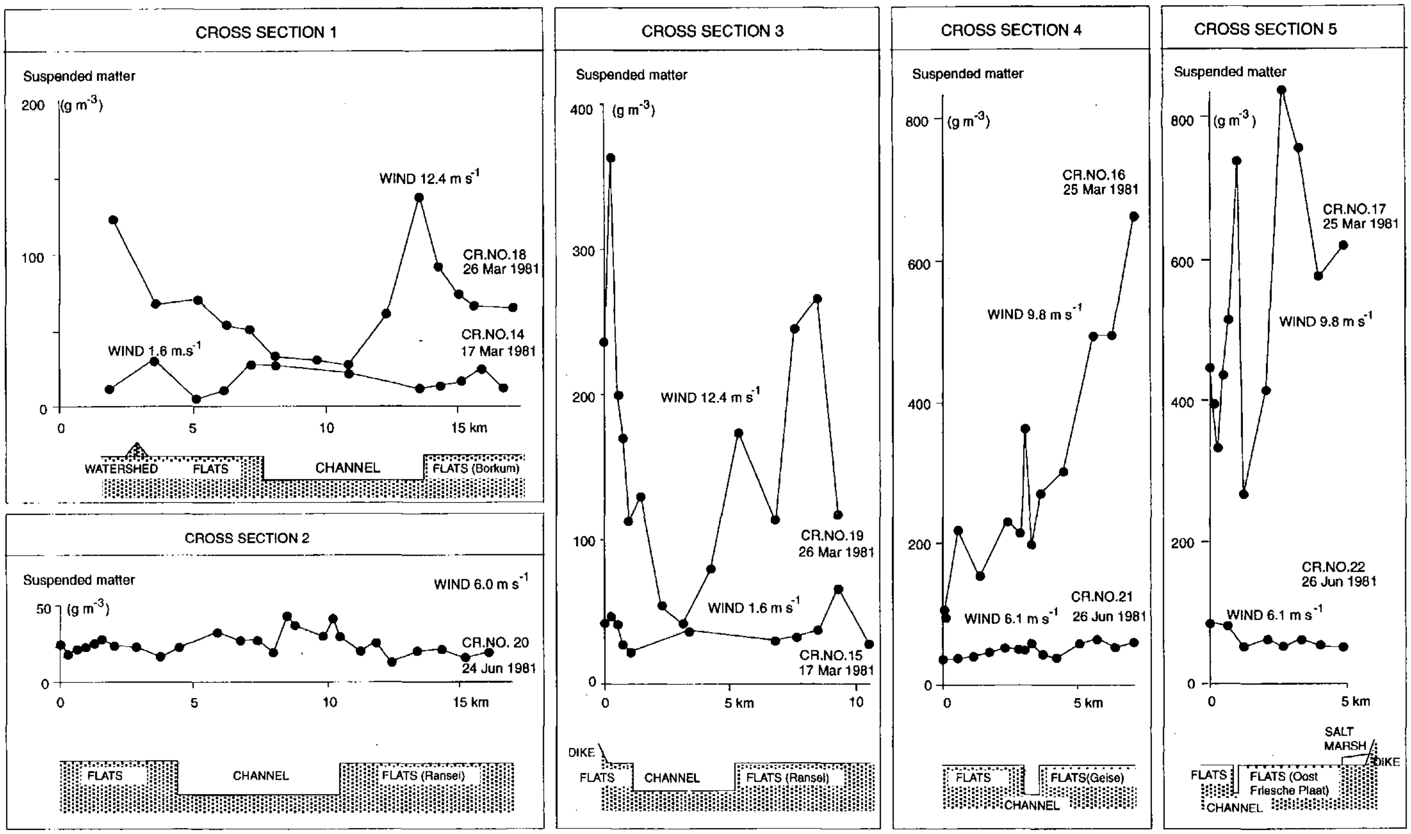

Fig. 2. Plot of the suspended matter concentrations as measured during the cross-sectional surveys and excluding cross-section 6 (which represents a channel). The different cross sections are located in Fig. 1B. The mean windspeed of the high-water period during sampling is given.

mine the statistical significance of observed relationships. It was also necessary, however, to derive mathematical descriptions of the trends. Therefore, the regression technique was applied. Multiple regression analysis was used to quantify the relationships between correlated variables: the combinations of "high-water windspeeds" and suspended matter or Chl *a*. Windspeeds from single high-water periods and combinations of subsequent high-water periods were used in the analyses. The high-water period during which sampling took place and the four high-water periods preceding sampling were used in the statistical analyses. In addition to regression analysis, the Durbin-Watson test and autocorrelation plots were applied to investigate the residuals for autocorrelation. According to the test requirements the homogeneity of the residuals and the normality of the distribution of residuals were also tested.

In a single case, it was necessary to test for the difference between two regression coefficients. This was done by *t*-test (Zar 1984). Statistical handling was mainly carried out with the SPSS 5.0 package.

Results

Assessment of resuspension and transport of mud and microphytobenthos from tidal flats—During periods of low windspeeds ($\lesssim 6$ m s^{-1}), most of the values for suspended matter in the channels and above the flats were similar, although the concentrations of suspended matter above the flats near the channel edges were usually lowest (Fig. 2). Maximum concentrations were found close to the dikes or the hydraulic boundary (tidal watershed) between the estuary and the adjacent tidal basins.

During periods of increasing wind and windspeeds $\gtrsim 6$ m s^{-1}, the highest values for suspended matter in the lower reaches of the estuary were found above the flat systems rather than in the main channel (Fig. 2, cross-sections 1 and 3).

During the March surveys in the shallow Dollard (Fig. 2, cruises 16 and 17), the southwesterly winds resulted in maximum values for suspended matter near the eastern margins of the Dollard (Geise and Oost Friesche Plaat). Figure 2 indicates that increases in windspeed from 1.6 or 6.1 m s^{-1} to 9.8 or 12.4 m s^{-1} produce a 4–5 × increase in suspended matter concentrations.

The drogue tracks (Fig. 3) show that the distance and the route traveled by the drogue were dependent on its starting point. Four of the drogues that started close to the shoreline (cruises 25–28) traveled only marginally in the main channel, in contrast to the drogues that started close to the main channel (cruises 23 and 29). The wind usually blew from the southwest, but during cruise 25,

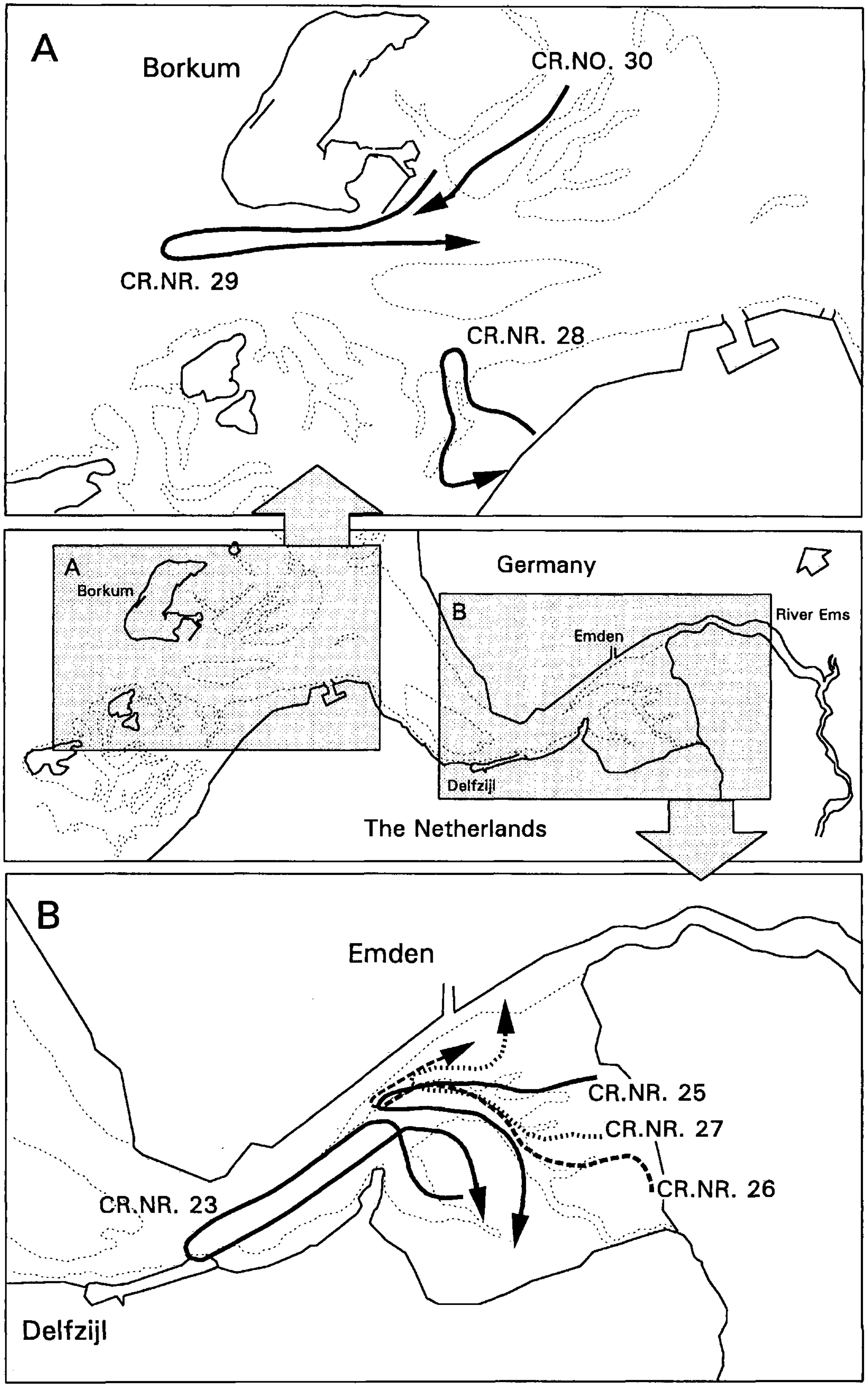

Fig. 3. Tracks of the drogues during some experiments.

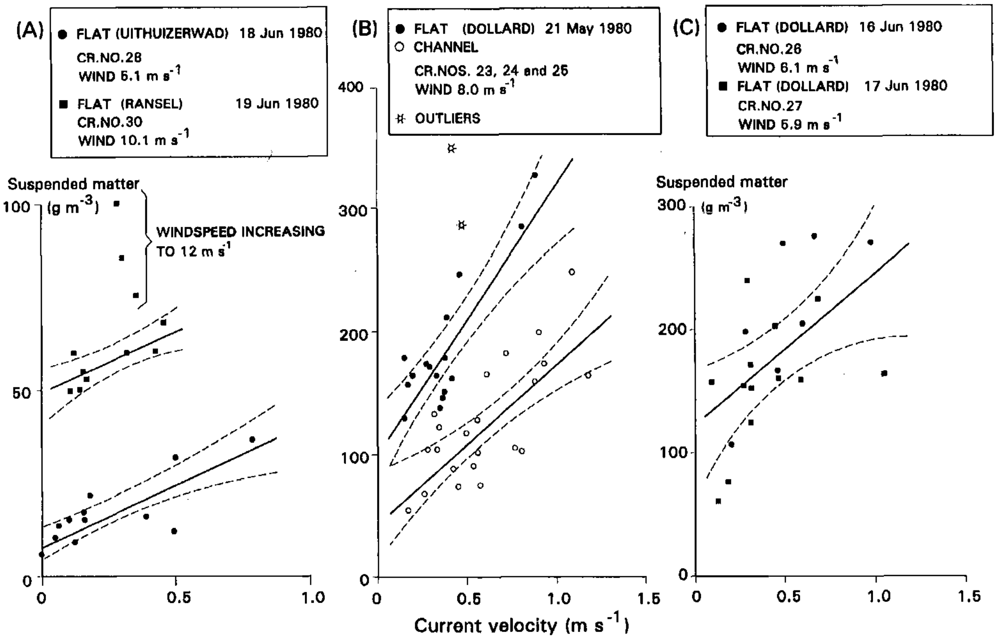

Fig. 4. Relation between current velocity and suspended matter concentrations for some drogue experiments. Outliers are indicated. Windspeed is mean value during the high-water sampling period. Confidence intervals are indicated by broken lines. Statistics are given in Table 2.

the northeasterly wind produced a different water circulation and consequently a different excursion of the drogue.

The correlations between the concentrations of suspended matter and current velocity are statistically significant (Table 2), suggesting that the current velocity above the intertidal flats and that in the channels (Fig. 4) contributes to resuspension of fine sediment. However, a doubling solely in windspeed from 5 to 10 m s^{-1} may be up to 5 times more effective in the resuspension process on the tidal flats than a doubling in current velocity from 0.5 to the maximum velocity of 1.0 m s^{-1} (cf. curves in Fig. 4A and cross-sections 1 and 3 in Fig. 2). The wind effect seems even more pronounced in the Dollard area. Increasing the windspeed from 6.1 to 9.8 m s^{-1} in the Dollard (Fig. 2; cross-sections 4 and 5) produced an eightfold increase in suspended matter, whereas increasing current velocity from 0.5 to 1 m s^{-1} (Fig. 4B and C) increased suspended matter by ~1–2 times.

These examples indicate that both the local current velocity and the local windspeed are responsible for resuspension of sediment but to a different degree. The effect of wind on the suspended matter concentrations appears to be predominant. The results of the regression analyses on suspended matter and current velocity are given in Table 2.

All the Chl *a* and suspended matter concentrations (Fig. 5) are significantly correlated in both the lower reaches of the Ems estuary (Fig. 5A, B; Table 2) and in the northern part of the Dollard (Fig. 5C, D; Table 2). However, in two of the three drogue tracks that crossed the southern part of the Dollard, the correlations are weak (Fig. 5E; Table 2) or absent (Fig. 5F; Table 2). One of the plots for the lower reaches (Fig. 5B; cf. also Figs. 2 and 4A) clearly demonstrates that the wind stimulates resuspension of Chl *a* as well as the mud fraction. Figure 5B–E also indicates that during higher windspeeds, concentrations of Chl *a* (and also of suspended matter) during the ebb period were generally higher than during the flood period, although at the lower windspeed (Fig. 5A), the opposite was observed. These different relationships are interpreted as an indication of resuspension (Fig. 5B–E) or settlement (Fig. 5A) of material. The differences in values between the ebb and the flood in Fig. 5 imply that both suspended matter and Chl *a* are transported in both directions between tidal flats and channels. When windspeeds are high, net transport is to the channels; when windspeed is low, transport is the opposite. Further, the correlation coefficients confirm that Chl *a* (microphytobenthos) and mud are resuspended and deposited simultaneously.

Quantification of resuspension—Concentrations of suspended matter and resuspended Chl *a* were quantified as a function of windspeed by processing measurements during high tide in the water above the tidal flats separately from those carried out in the main channels. This difference in processing was because the wind has a direct effect on the suspended matter concentrations in the shallow (<2 m) water above the tidal flats (Fig. 6A) but not necessarily on concentrations in the water of the deep (7–25 m) main channels (Figs. 6B and 7).

For the lower reaches of the estuary (sectors II–IV) and for the Dollard (sectors VII, VIII, X, and XI), the mean concentrations of suspended matter in the water mass

Table 2. Results of regression analysis applied to different data whose values are plotted in some figures. n—number of observations; $\bar{x}$—mean X value; $\bar{y}$—mean Y value; a—y intercept; b—regression coefficient representing the curve slope; r_s—Spearman rank correlation coefficient; P—significance level of r. The last column gives the figures in which the basic data have been plotted. SPM—Suspended matter (g m^{-3}); Chl a—chlorophyll a (mg m^{-3}); wind—windspeed (m s^{-1}); SPM-flats—suspended matter concentrations above tidal flats (g m^{-3}); % resusp. Chl a—resuspended microphytobenthos from the top 0.5 cm of sediment (%).

X	Y	Area	Cruise	n	$\bar{x}$	$\bar{y}$	a	b	r_s	P	Fig.
SPM channels	Chl a	Lower reaches	1	4	66.2	1.4	−0.12	0.02	0.183		—
		Dollard	1	5	102.6	4.1	−1.84	0.06	0.9996	<0.001	—
		Lower reaches	5–10	22	46.1	1.4	0.74	0.01	0.557	$0.001 < P < 0.01$	—
		Dollard	5–10	24	197.6	4.5	−0.68	0.02	0.89	<0.001	—
SPM channels	Chl a	Lower reaches	28	14	17.4	5.9	2.51	0.19	0.808	<0.001	5
		Lower reaches	29, 30	27	28.3	16.2	8.29	0.27	0.943	<0.001	5
		Dollard	24	11	164.1	34.4	22.31	0.07	0.826	<0.001	5
		Dollard	23	17	159.8	34.8	24.20	0.07	0.724	<0.001	5
		Dollard	26, 27	24	171.3	5.4	3.40	0.01	0.238	>0.1(ns)	5
		Dollard	25	15	140.0	59.8	61.58	−0.01	0.132	>0.1(ns)	5
Current velocity	SPM channels	Lower reaches	28	12	0.3	17.8	10.16	29.27	0.784	$0.001 < P < 0.01$	4
		Lower reaches	30	8	0.2	58.3	49.63	34.50	0.799	$0.01 < P < 0.02$	4
		Dollard flats	23, 24, 25	16	0.4	187.0	103.6	225.4	0.865	<0.001	4
		Dollard channels	23, 24, 25	22	0.6	125.3	52.0	120.1	0.755	<0.001	4
		Dollard	26, 27	20	0.4	179.4	121.4	127.9	0.557	$0.01 < P < 0.02$	4
Wind	SPM flats	Lower reaches		8	6.8	56.6	−14.24	10.43	0.724	$0.01 < P < 0.05$	6
		Dollard		9	7.7	243.9	−386.88	81.57	0.804	$0.001 < P < 0.01$	6
Wind	SPM channels	Lower reaches		11	8.0	47.5	7.68	4.98	0.756	0.006	6
		Dollard		11	5.7	182.6	28.51	27.25	0.804	0.004	6
Wind	% resusp. Chl a	Lower reaches		5	8.6	33.6	−20.71	6.30	0.966	$0.001 < P < 0.01$	—
		Dollard		4	5.8	23.5	−11.54	6.04	0.959	$0.02 < P < 0.05$	—
		Total estuary		9	7.4	29.1	−10.77	5.41	0.945	0.0001	7

above the tidal flats were plotted against mean windspeed during the high-water sampling period (HW0) (Fig. 6A and Table 2 for statistics). The coefficients of variation in the X and Y values ranged between ~40 and 110%. Despite the variation in Y values, the correlation coefficients were positive and high and statistically significant (Table 2), indicating a positive correlation between parameters. Figure 6A indicates that resuspension in the lower reaches occurs at windspeeds of ~1 m s^{-1}, while in the Dollard, it starts at windspeeds >5 m s^{-1}. The regression coefficient (slope) for the Dollard is fivefold greater than that of the lower reaches. However, in general, winds from the north and northeast (indicated in Fig. 6A) stimulate resuspension less than do winds from the opposite directions (S–SW) because of differences in sediment composition and cohesiveness. The observed difference in the onset of resuspension between the Dollard and the lower reaches (Fig. 6A) is because nearly half of the observations available for the Dollard refer to wind directions between N and NE.

The drogue experiments (Fig. 3) indicated that depending on the starting position, the water running above the tidal flats during high tide does or does not reach the central part of the channel. These differences in drogue tracks and the absence of irregular track patterns indicate that during a single tide, the water from the tidal flats is not thoroughly mixed with channel water. A comparable conclusion can be drawn from the lateral mud distribution during the cross-section observations (Fig. 2). Thus, it is expected that resuspension of mud from tidal flats will not immediately result in increased suspended matter concentrations in the central part of the main channels.

The expected time lag between the resuspension of mud from tidal flats and the response of the suspended matter

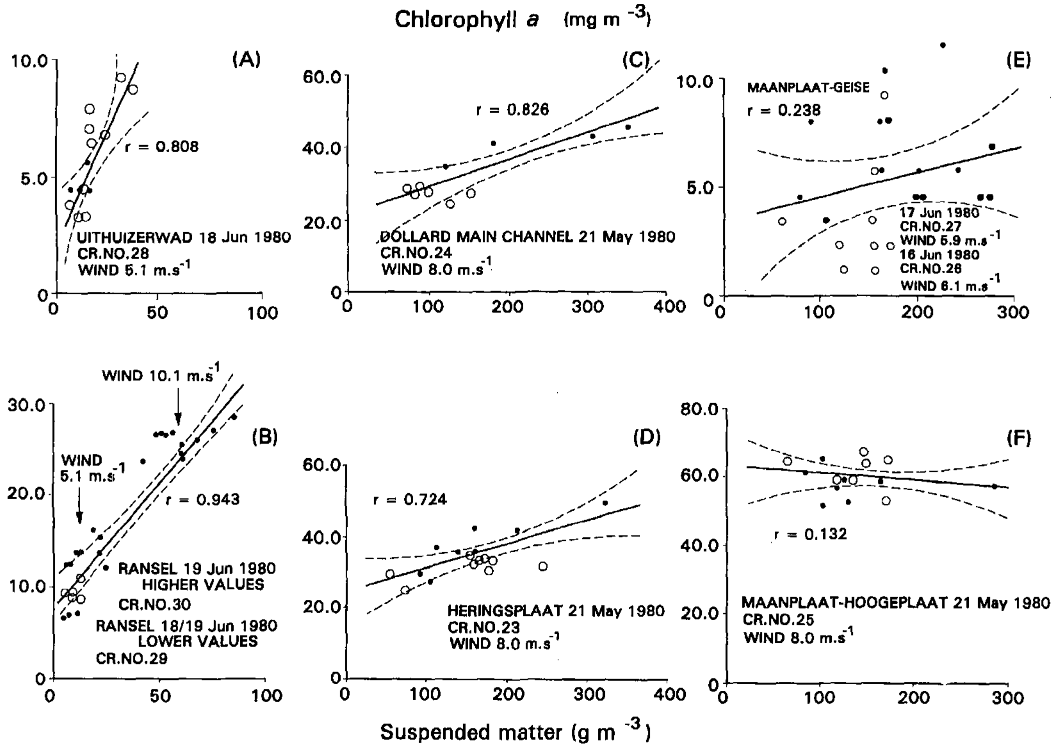

Fig. 5. Plots of concentrations of Chl *a* against concentrations of suspended matter for the drogue experiments (cf. Fig. 3). Mean windspeed during the high-water sampling period is given. Ebb period—●; flood period—○. Broken lines indicate confidence intervals. Statistics are given in Table 2.

concentration along the axis of the main channels was investigated with multiple regression analysis. The data used were from the longitudinal surveys because, reach by reach, the entire estuary was sampled (*see materials and methods*).

For the areas investigated (lower reaches and Dollard), a generally applicable equation emerged for suspended matter measured along the main axis of the estuary as a function of windspeed. The relation was obtained when linear regression analysis was applied and did not improve further by additional multiple regression analysis. The highest and statistically significant correlations between windspeed and suspended matter for the two areas were obtained for the mean windspeed during the three high-water periods preceding sample collection (HW1+2+3) (Table 3). This windspeed was called "effective windspeed." Despite the low number of observations (11 instead of the required 14), the Durbin-Watson test was applied to investigate residuals for autocorrelation. Additionally, autocorrelation plots were made. From both approaches, no indications for autocorrelation were obtained for the data from the two areas under investigation. Further, the distribution of residuals was tested and appeared not to differ from a normal one, as was concluded from the normal probability plots. The statistics in Table 3 show that the regression coefficients b for both areas are statistically highly significant (P_b), while the intercept values a are not (P_a). The regression equations obtained explain between 57 and 65% of the variance (Table 3).

Figure 6B gives the concentration of mean suspended matter in the channels per survey per area (lower reaches and Dollard) plotted as a function of effective windspeed (HW1+2+3) as well as the regression equation. The wind was mainly south to southwesterly; deviating wind directions are indicated in Fig. 6B. As with observations in the water above the tidal flats (Fig. 6A), northerly and easterly winds in the Dollard produced a somewhat lower resuspension of mud than did southerly to southwesterly winds (Fig. 6B). The coefficients of variation in the mean suspended matter concentrations and windspeeds were relatively small and ranged from 38 to 42%. The relationships in Fig. 6B indicate that about three tidal cycles (the lateral mixing scale) are needed to transport fine suspended matter (mud) from the tidal flats to the axis of the main channels and vice versa.

The relationship between windspeed and resuspended Chl *a* derived from microphytobenthos was also investigated for the lower reaches of the estuary and the Dollard. The most suitable expression of the resuspended amount was the fraction of the Chl *a* mass present in the water of the sectors under consideration. The total mass was defined as the sum of the mass present in the total water volume per area and the mass present in the top 0.5 cm of the sediments of the tidal flats situated above mean low-water level per area. Because of the few data,

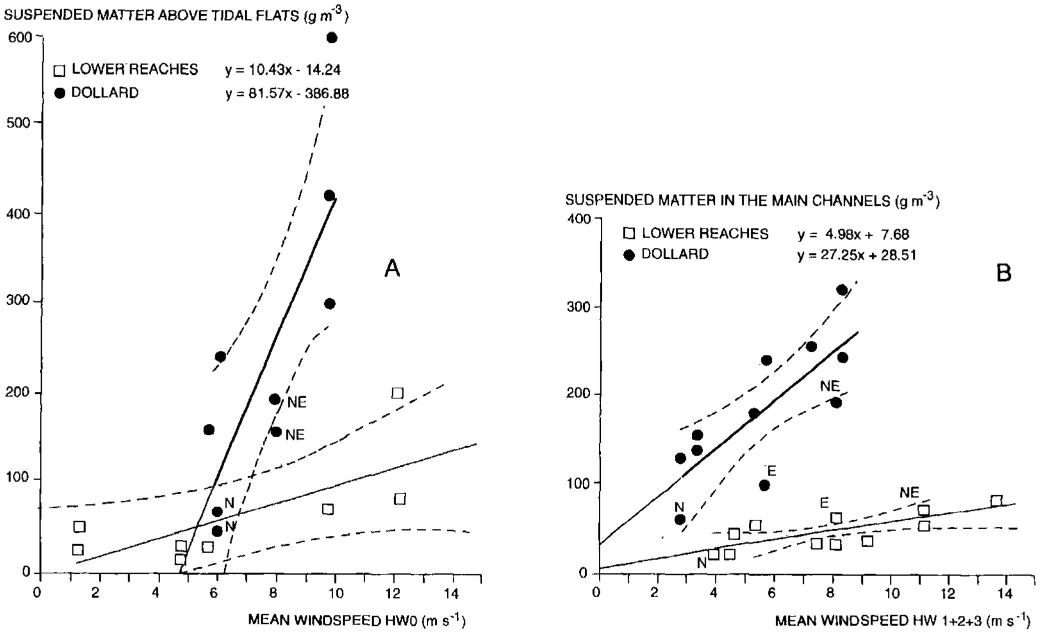

Fig. 6. Relation between mean suspended matter concentrations in the water above the tidal flats during high tide and the mean windspeed during the same high-water sampling period (HW0) in two parts of the Ems estuary (A) and the water of the main channels and the mean windspeed during three high-water periods preceding sample collection (HW1+2+3) in two parts of the estuary (B). Confidence intervals are indicated. Statistics are given in Table 2. Values are derived from surveys 24–30 and 1–11 and 20, respectively.

the biomass values of station HW near the boundary between sectors IV and V were also used when calculating the resuspension of microphytobenthos in sectors II–IV. Table 4 gives the mean concentrations of microphytobenthos Chl *a*, the fraction of the Chl *a* in the water (% resuspended microphytobenthos), and the effective windspeed (HW1+2+3) relevant to the Chl *a* sampling. Regression equations were calculated for the lower reaches and the Dollard (Table 2). According to the *t*-test, the regression coefficients of both areas are not statistically different (*t*-value 0.038 and $P > 0.10$).

Because of the low number of observations, only the autocorrelation plot was used to investigate the residuals for autocorrelation. No indication for autocorrelation was obtained, although the distribution of residuals was homogeneous. The statistics in Table 3 show that the regression coefficient *b* was statistically highly significant (P_b), but the intercept value *a* was not (P_a). The obtained regression equation explains 89% of the variance (Table 3).

Thus, for both the lower reaches and the Dollard, the resuspended fraction of total Chl *a* can be described as a linear function of effective windspeed by use of only one linear equation (Fig. 7). This equation allows the calculation of the amount of resuspended microphytobenthos as a function of windspeed during any period, even in summer, when phytoplankton Chl *a* far exceeds the contribution from resuspended microphytobenthos.

Discussion

Resuspension of sediment and microphytobenthos—The equations in Figs. 6 and 7 represent simple models to

Table 3. Results of linear regression analysis between suspended matter concentrations in the main channels and windspeed for the three high-water periods preceding sampling. r_s—Spearman rank correlation coefficient; r^2—explained variance; *b*—regression coefficient (slope); SE—standard error; *a*—intercept; *P*—significance level.

Parameter/area	r_s	r^2	b	SE b	P_b	a	SE a	P_a
Mud								
Lower reaches	0.756	0.572	4.98	1.39	0.006	7.68	11.82	0.532(ns)
Dollard	0.804	0.646	27.25	7.14	0.004	28.51	43.08	0.525(ns)
Microphytobenthos								
Both reaches	0.945	0.893	5.41	0.71	0.0001	−10.77	5.54	0.093(ns)

Table 4. Mean Chl *a* concentrations measured in the top 0.5 cm of tidal flats and in water, percentages of Chl *a* in the water compared with the sum of the Chl *a* present on the tidal flats and in the water, and effective windspeeds.

Sampling date	Mean Chl *a* (mg m^{-2})	Chl *a* in water (%)	Effective windspeed (m s^{-1})
Lower reaches			
8 Feb 80, flats	31.8		
4 Feb 80, water	11.6	27	8.2
18 Mar 80, flats	18.2		
19 Mar 80, water	20.4	53	10.9
3 Dec 80, flats	12.7		
2 Dec 80, water	6.8	35	8.2
16 Mar 81, flats	57.8		
16 Mar 81, water	5.1	8	4.6
24 Mar 81, flats	23.9		
23 Mar 81, water	19.6	45	11.2
Dollard			
8 Feb 80, flats	35.4		
4 Feb 80, water	8.8	20	5.8
18 Mar 80, flats	44.4		
19 Mar 80, water	30.2	41	8.2
3 Dec 80, flats	42.0		
2 Dec 80, water	11.2	21	5.8
16 Mar 81, flats	66.5		
16 Mar 81, water	8.6	12	3.4
24 Mar 81, flats	—		
23 Mar 81, water	10.8	?	8.4

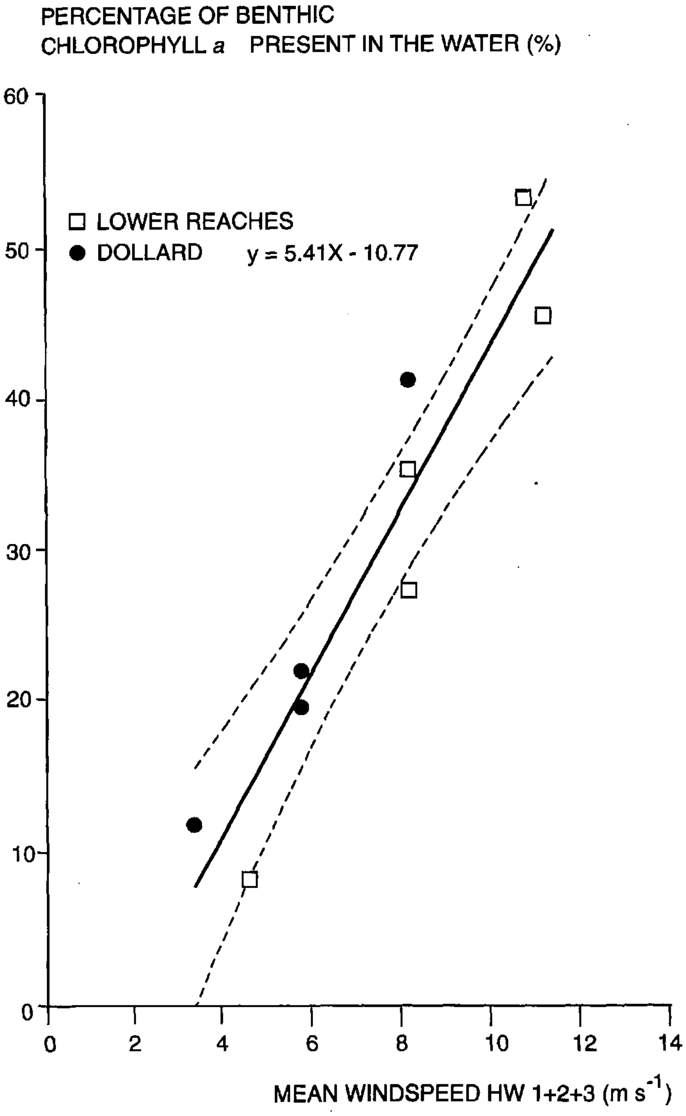

Fig. 7. Relation between the fraction of resuspended Chl *a* (mainly benthic diatoms) and mean windspeed during the three high-water periods preceding sample collection (HW1+2+3) for the lower reaches and the Dollard area. The resuspended Chl *a* fraction is *Bw*(*Bw* + *Bb*) × 100, where *Bw* is Chl *a* mass in the water of a certain sector and *Bb* is the Chl *a* mass present in the top 0.5 cm of the tidal flats in the same sector. Confidence intervals are indicated. Basic data are given in Table 4 and statistics in Table 3.

calculate large-scale resuspension in the Ems estuary. With these equations, only data on local windspeed are required to estimate suspended matter concentrations. The ~5 times steeper slope in mud resuspension for the Dollard as compared with that for the lower reaches of the estuary is in accord with the strong difference in the fine (<55 μm) sediment fraction of the tidal flats between both areas: the higher the concentrations of the fine sediment fraction, the more fine sediment (mud) will be resuspended. Thus, resuspension is dependent on the sediment composition of the tidal flats, something that can be incorporated easily in the equations presented.

The fact that the slope of the wind-induced resuspension of mud from the tidal flats during high water (Fig. 6A) is steeper than the equivalent slope for the main channels (Fig. 6B) emphasizes the greater sensitivity of the shallow tidal flat systems to wind. These tidal flat systems can be considered the main source of resuspended mud during windy weather (cf. Fig. 2), whereas they must function as important deposition areas during calm weather.

That the suspended matter concentrations in the main channels (Fig. 6B) can be calculated from windspeed according to a linear function without necessarily considering the loss of mass of mud from the intertidal sediments due to resuspension means that under the study conditions, the tidal flats represented an infinite source for mud. The sediments are, however, certainly not an infinite source for microphytobenthos (Fig. 7), where resuspension is a function of both windspeed and available amount of biomass per reach in the top 0.5 cm of sediment. The difference between the two relations is explainable because microphytobenthos occurs mainly in the top centimeter and declines with depth (de Jonge and Colijn 1994), while mud occurs in about the same concentrations at all depths.

Because windspeed in the lower reaches is, on average, higher than in the Dollard and resuspension of microphytobenthos for both areas follows the same equation, the resuspension of these algae is more important in the lower reaches than in the Dollard area.

The nature of the relation between windspeed and suspended matter is unclear for windspeeds <3 m s^{-1} and >13 m s^{-1} (*see Fig. 6*). As Demers et al. (1987) and others have suggested, there may be a threshold value of windspeed somewhere between 0 and 3 m s^{-1} below which sediment is not resuspended. The values referred to in the various studies were obtained from shallow subtidal systems and not from tidal flat systems. For tidal areas, it is not easy to relate resuspension to wind-induced waves because of the changing water depth during the tidal cycle (Carper and Bachmann 1984).

Kamps (1962) measured the relation between mean windspeed and clay content in the water column near high tidal flats just in front of land reclamation works in the Netherlands. From his data, it could be inferred that the lowest clay content occurs at a mean windspeed of ≤ 1 m s^{-1}. The present data indicate that the wind threshold value in the Ems estuary is <3 m s^{-1} (Fig. 6B). From the relation between effective windspeed and resuspension of microphytobenthos (Fig. 7), this threshold value can be estimated to be at a windspeed of 1–2 m s^{-1}. These observations correspond very well with the findings of others. Linear extrapolation of the regressions in Figs. 6B and 7 for windspeeds <3 m s^{-1} and >13 m s^{-1} is statistically invalid. Above 13 m s^{-1}, the regression line might deflect toward a saturation level at high windspeeds because all mobile sediment is suspended. But in the Elbe estuary, under westerly winds blowing from the sea, Dücker (1982) found a sharp increase in suspended matter for a windspeed between 12.3 and 20 m s^{-1} instead of a deflection.

Although suspended matter was not sampled within 1 or 2 cm from the sediment bed of the tidal flat, the observations presented in Fig. 6A and B are consistent with the Yalin bedload equation (cf. Drake and Cacchione 1989) in which the near-bed reference concentration is a function of certain parameters that include the volume concentration of resuspendible material in the bed.

The relationship between suspended matter concentrations in the main channels and the average windspeed over the three high-water periods preceding sample collection (Fig. 6B) indicates that wind is an important factor in the resuspension process. Tidal currents are of minor importance when considering the ranges in tidal currents and in windspeed (Fig. 4; *see also* Demers et al. 1987). In terms of resuspension, the Ems estuary seems to behave like a simple system consisting of a sediment compartment and a water body making contact twice a day. During periods of high windspeed, strong wave action, and thus high orbital (wave-induced) current velocity, a relatively large part of the mud fraction and microphytobenthos in the superficial sediment layer is resuspended. The resuspended material is transported to the main channels by the ebb currents, after which it is dispersed by mixing. Thus, the initial redistribution of resuspended sediments may depend on the location of the tidal flats within the current field, while further transport is achieved by estuarine mechanisms of accumulation (Postma 1967; Dronkers 1986).

As indicated, the best fit between either suspended matter or microphytobenthos in the main channels and windspeed (Fig. 6B) also implicitly gives an approximate estimate of the local time scale for lateral mixing. From the drogue tracks (Fig. 3), it can be inferred that this mixing must last longer than one tidal period. The tracks show that a water mass close to the mainland or tidal watershed rarely reaches the main channel at low tide, whereas water close to the main channel reaches even the middle part of some channels. Combining this finding with the results in Fig. 6B indicates that the lateral mixing time scale of the water masses is ~3 tidal cycles for both the Dollard area and the lower reaches, despite the hydrographical differences between the two areas.

Ecological consequences—There are several ecological consequences of the relationship between effective windspeed and resuspended fraction of microphytobenthos. Over 50% (Fig. 7) of the microphytobenthos biomass in the top 0.5 cm of sediment can reach the main channel when windspeed reaches values of 12 m s^{-1}. For the microphytobenthos, the same processes operate as for mud, which implies that in coastal ecology, serious attention must be paid to the phenomenon of co-occurrence of benthic diatoms in both the benthic and the pelagial regions. This knowledge is an important extension of previous information (de Jonge 1985). During winter, when phytoplankton biomass is very low and microphytobenthos is still present (Colijn and de Jonge 1984; de Jonge and Colijn 1994), resuspended microphytobenthos can play an important role as a food source for grazers in the water column (de Jonge and van Beusekom 1992).

The reported effects of current velocity and windspeed on the resuspension of microphytobenthos can be roughly converted to an average annual value. The mean annual windspeed in the lower reaches is ~6.5 m s^{-1}, and in the more sheltered Dollard it is 4.5 m s^{-1}; the result is that, on average, 14–25% of the total biomass of benthic diatoms is in suspension. The proper value may be even higher because the resuspension is dependent on mean windspeed during high tide (effective windspeed) and not on mean windspeed—a point that will be addressed elsewhere.

Earlier, we roughly compared the effect of water currents with the effect of wind on the resuspension of mud and concluded that under the given ranges in windspeed and current velocity, the resuspension due to wind was much more effective than that due to the currents. Because of the strong similarities in resuspension of mud and microphytobenthos, this conclusion also holds for the algae. Because there is no other information on current velocities above the tidal flats and because there is no indication that our results did not represent mean conditions, we conclude from Figs. 4 and 6B (cf. Table 2) that the resuspension of mud (and consequently also of benthic diatoms) is mainly governed by wind effects. As indicated, the important role of the tidal current is to transport the material back and forth between the tidal flats and the main channels.

Water column production is usually ascribed to phytoplankton. Our results imply that when, on average, 14–25% of the microphytobenthos biomass is present in the water column, we are dealing with an amount that on an annual basis (cf. Colijn and de Jonge 1984; de Jonge and Colijn 1994) represents ~20–25% of the suspended Chl *a*. The only assumption made here is that suspended populations of benthic diatoms do grow as efficiently as benthic populations. Results to be published elsewhere support this assumption.

The above examples also imply that in ecological simulation models, both turbidity and resuspension of microphytobenthos can be modeled as a function of windspeed. In this way, realistic fluctuations in light attenuation and acceptable fluxes of microphytobenthos can be calculated. The assumption that a constant portion of the newly produced organic matter is resuspended irrespective the wind conditions (Baretta and Ruardij 1988) can thus be refined.

Sediment stability—A positive effect of microphytobenthos biomass on sediment stability has been observed under laboratory conditions and under field conditions (Vos et al. 1988; Delgado et al. 1991). Seasonal changes in sediment stabilization can be attributed to seasonal changes in algal biomass (Frostick and McCave 1979). Some investigators have suggested that mucus exuded by benthic algae can inhibit sediment transport because it stabilizes the sediment bed (Neumann et al. 1970; Holland et al. 1974; de Boer 1981; Grant et al. 1986; Paterson 1989). Others (Daborn et al. 1993) have shown that disturbance of an existing situation can lead to a cascade of effects in a benthic ecosystem.

The results here show that under given field conditions and considering large areas, there is no clear indication that a greater microphytobenthos biomass on the tidal flats results in the sediment bed being significantly more stable (cf. Table 4 and Fig. 7). Our data also show that the response of suspended matter to windspeed changes was very rapid, which means that under natural estuarine conditions, sediment (microphytobenthos included) is rapidly exchanged between the tidal flats and the overlying water. Apparently, a mosaic of patches is present where sediments are stabilized by microphytobenthos and accompanying structures (bacteria, fungi, and exudated products). Further, there are patches where sediment is readily resuspended because of, for instance, low concentrations of microphytobenthos or increased bed roughness due to (e.g.) bioturbation and biodeposition. The approach used here may be applicable to other estuaries.

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Submitted: 30 May 1991
Accepted: 23 September 1994
Amended: 20 January 1995