Netherlands Journal of Sea Research
32 (2): 173-182 (1995)

FRACTAL GEOMETRY OF *IN SITU* FLOCS IN THE ESTUARINE AND COASTAL ENVIRONMENTS

SHUMIN CHEN and DOEKE EISMA

Netherlands Institute for Sea Research, P.O. Box 59, 1790 AB Den Burg, Texel, The Netherlands

ABSTRACT

One- and two-dimensional fractal dimensions of *in situ* flocs were determined from the dependence of the area and perimeter of projection of the flocs on their greatest length, using an underwater camera and image-analysis system. Values for the fractal dimensions of flocs in the Elbe estuary and the North Sea varied among the samples: D_1 in the range of 1.03 to 1.14 and D_2 in the range of 1.41 to 1.81. D_2 as obtained here represents the three-dimensional fractal dimension of flocs, which has been obtained in previous studies from the dependence of settling velocity or porosity of flocs on their characteristic length. Comparisons of environmental factors showed no relationships between the fractal dimension and fluid shear. Salinity effects on the fractal dimension were probably also insignificant in our samples. The relationship of D_1 with the concentration of suspended matter was fairly convincing and suggests that the flocs had a rougher edge of projection at high than at low concentrations.

Key words: fractal dimensions, *in situ* flocs, image analysis, North Sea, Elbe

1. INTRODUCTION

Flocs in suspension in estuarine and coastal waters have recently been investigated by means of *in situ* underwater photography (Eisma *et al.*, 1991a; Eisma & Li, 1993; Chen *et al.*, 1994). Such flocs consist of mineral grains, biogenic debris and rather fluffy organic material. Pictures from an *in situ* camera and from scanning electronic microscopy show them to be of a highly irregular shape and disordered nature, with the area-equivalent sizes ranging from a few micron to a few mm. Our results so far have indicated that with respect to size distribution, the formation of these flocs is typically a physical process in which aggregation by differential settling of particles/flocs and by fluid shear play key roles (Eisma & Li, 1993; Chen *et al.*, 1994). This finding strongly suggests that differences in the geometric structure of flocs in estuarine and coastal waters can be distinguished by applying fractal theory (Meakin, 1991).

The structures of real fractal flocs are scale invariant or self-similar in the statistical sense. The number of particles (N) in a fractal floc is proportional with some power to the characteristic length of the floc (l) (Meakin, 1988). This relationship can be expressed as

$$N \sim l^D \qquad \text{(eq. 1)}$$

where D is the fractal dimension of the floc. For a Euclidean object such as a sphere, D=3. Flocs aggregated by random processes have fractal dimensions significantly less than the Euclidean 3. For instance, Li & Ganczarczyk (1989) have determined the effective fractal dimension for a variety of aggregates generated by wastewater treatment using published data for the dependence of the settling velocity on the characteristic aggregate radius. Values of D in the range of 1.4 to 2.8 were obtained. For the effective fractal dimension of flocs in aquatic systems, Logan & Wilkinson (1990) estimated 1.26 for *in situ* marine snow, 1.78 for estuarine flocs and 1.94 to 2.14 for oceanic biological aggregates, indicating that the order of the fractal dimensions is: *in situ* marine snow < estuarine flocs < oceanic aggregates.

Besides quantifying the complex structures of flocs, fractal theory dealing with flocculation processes can potentially identify the aggregation mechanism as well as the cohesive efficiency of the particles com-

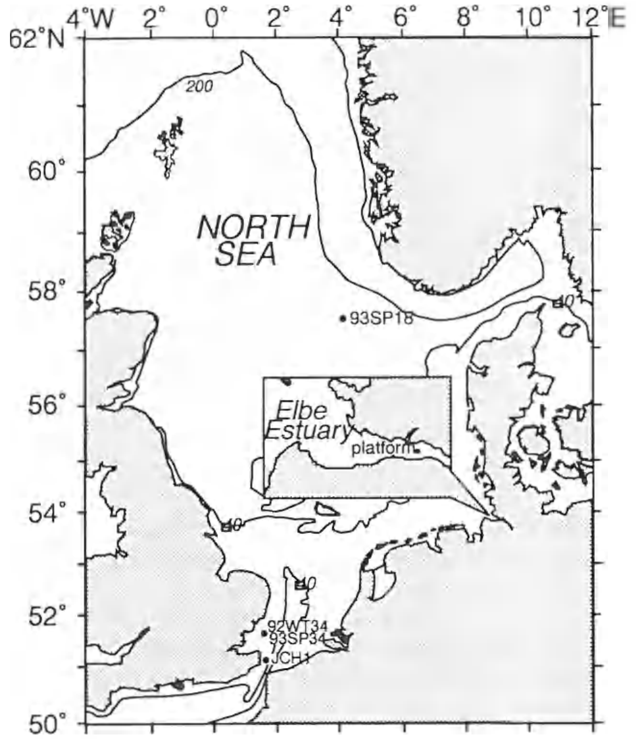

Fig. 1. Map of sampling positions. Three samples were taken from an anchor platform in the Elbe estuary and seven samples were taken from the North Sea.

posing the flocs. In the case of colloidal aggregation of inorganic particle systems, two distinct, limiting types have been characterized by the fractal dimension (Lin *et al.*, 1989). One type of aggregation is rapid and results in highly tenuous structures of aggregates. It is referred to as diffusion-limited colloidal aggregation (DLCA) because of the negligible repulsive force between colloidal particles. The fractal dimensions for this type of aggregates are around 1.8. Another type of aggregation is slow because its rate depends on the time required for the colloidal particles to overcome a substantial repulsive barrier. This aggregation is classified as reaction-limited colloidal aggregation (RLCA) and forms aggregates with D values around 2.1. For flocs in aquatic systems, a fractal classification with respect to particle relative motion resulting in aggregation was given by Jiang & Logan (1991). The authors calculated from theoretical steady-state size distributions that fractal dimensions of aggregates formed solely by fluid shear are higher than 2.4, and that those formed solely by differential settling are between 1.6 and 2.3.

The results introduced above, as well as many computer simulations (see review by Meakin, 1988) have demonstrated that the application of fractal theory to flocculation processes provides a unique approach to characterizing the complex structures of flocs in quantitative terms and, more significantly, is quite promising to understand the aggregation mechanisms by which the flocs are formed. Most flocs in estuarine and coastal waters are found to be fragile and are aggregated by random processes (Eisma *et al.*, 1991a; Eisma & Li, 1993; Chen *et al.*, 1994). It is, therefore, most likely that these flocs are fractal. Their aggregation processes may be analogous to the simple limiting-case models such as DLCA and RLCA.

It should be emphasised that an *in situ* technique is necessary to deal with the fractal dimension of flocs in estuarine and coastal waters. Because of the fragile nature of the flocs, they are easily broken up due to shear created during sampling and experimental measurements. Besides floc break-up, restructuring of flocs may be caused by inevitable disturbances during the sampling and measurements, which changes the fractal dimension (Meakin, 1988). For example, some values of fractal dimension obtained from biogenic aggregates cultured in a laboratory reactor were thought to be too high because of aggregate restructuring during experiments with strong mixing (Logan & Wilkinson, 1990). It seems that the fractal dimension of flocs is sensitive to the surrounding hydrodynamic conditions when, as well as after, the flocs are formed.

2. MATERIAL AND METHODS

2.1. THEORETICAL CONSIDERATIONS

In situ size measurements of flocs by underwater photography are being done extensively at present. Image analysis of photographs of flocs can give quite accurate data for the area, perimeter and greatest length of projection of the flocs. Based on data obtained from such *in situ* measurements, we assume that the scaling relationships between the perimeter (P) of the image of a projected floc and its greatest length (l), and between the area (A) of the image and l are given, respectively, by

$$P \sim l^{D1} \qquad \text{(eq. 2)}$$

and

$$A \sim l^{D2} \qquad \text{(eq. 3)}$$

where D_1 is defined as the one-dimensional fractal dimension of the projection of the floc and D_2 as the two-dimensional fractal dimension. The value of D_1 (or D_2) can be calculated from the slope in a log-log plot of A (or P) *versus* l. For a perfect, infinite fractal, D_2 is equal to the three-dimensional dimension, D_3, of the parent fractal, if $D_3 < 2$; but it is reduced to dimension 2, if $D_3 \geq 2$ (Meakin, 1988). This property provides a way to obtain the dimensions of fractals with $D_3 < 2$ from their projection dimensions, and is applied here.

TABLE 1
Sampling information and environmental factors of samples.

sample	*sampling location*	*sampling date*	*sampling depth*	*water depth (m)*	*salinity (‰)*	*current velocity ($m \cdot s^{-1}$)*	*concentration ($mg \cdot dm^{-3}$)*	*organic content (%)*
E1415	Elbe estuary	6-11-91	surface	-	9.1	0.06	71	15.5
E1530	Elbe estuary	6-11-91	surface	-	7.3	0.85	63.3	10.9
E1520	Elbe estuary	6-11-91	bottom	-	7.4	0.70	156	13.5
JCH1	southern N.S.	6-23-93	5 m	29.5	35.15	-	9.6	21
92WT34	southern N.S.	1-27-92	surface	42.7	35.00	-	30	12.6
92WT34	southern N.S.	1-27-92	bottom	42.7	35.00	-	51.7	11.3
93SP18	central N.S.	3-26-93	surface	67.5	35.05	-	3.1	22.6
93SP18	central N.S.	3-26-93	bottom	67.5	35.05	-	2.6	15.7
93SP34	southern N.S.	4-1-93	surface	43.0	34.73	-	7	8.2
93SP34	southern N.S.	4-1-93	bottom	43.0	34.75	-	38.2	12.1

2.2. SAMPLING

Three samples were taken from the Elbe estuary in June 1991 and seven samples from two regions in the North Sea during 1992-93. Sampling positions are shown in Fig. 1. Photographs that give the projection of flocs were taken with a 1:1 *in situ* underwater camera developed at NIOZ (Eisma *et al.*, 1990). During photographing, the flocs were not disturbed so that their geometric structures remained in their natural state. At least five photographs were taken for one sample from the surface water as well as from the bottom water: the time interval between two photographs was around 12 sec and between two sampling depths 3 to 4 min.

Along with photographing, salinity and current velocity were measured *in situ* at 5 m water depth (for the Elbe estuary only). Water samples were collected with a Niskin bottle, around 10 min before or after the photographs were taken. Filtration of the water samples without net screening was carried out on board, using pre-weighed 0.4-µm Nuclepore filters. In the laboratory, the concentration of suspended matter was determined by dry weight (the samples were dried at 55°C for a few days). The organic content was estimated by weight using a combustion method: the samples were ashed at 550°C over 8 hours. These environmental factors and other sampling information are shown in Table 1.

2.3. IMAGE ANALYSIS

To avoid photograph variation, at least four photographs of each sample were analysed using an image-analysis system. The system, developed at NIOZ (Eisma *et al.*, 1990), consisted of a microscope, video camera, monitor, personal computer and image-analysis software (TIM, version 3.36, Difa Measuring Systems). The TIM provided a window of 512 by 512 pixels on the monitor. One pixel was calibrated to be a 10.87 by 7.549 µm rectangle on the base of a microscopic lens and the 1:1 camera photograph. A complete photograph was divided into 24 sections and these were analysed one by one. Before the analysis, the section to be analysed was amplified by the microscope and transferred to the monitor by the camera. The picture on the monitor was then converted into 256 gray scales and was thresholded to a binary image (black and white) by the TIM. A thresholding value was chosen to define floc images from the originals which were meanwhile seen on the monitor. Because of differences in contrast between the flocs in the photograph, it was impossible to obtain all floc images from the picture without exaggerating the size of those of high contrast. We chose those of high contrast for the thresholding, and thus a number of flocs of low contrast were lost. Besides, the floc images lying on the border between the sections were recognized and removed because they were not complete. Both these losses in obtaining floc images, however, were equivalent to taking a lower number of flocs from a sample, and will not have influenced the results as long as the number of flocs analysed is for sufficient statistical purposes. An example of the thresholding procedure is shown in Fig. 2.

Once the thresholding value was chosen, the TIM counted the number of pixels in the image to obtain the area. The perimeter and greatest length were computed by the TIM from the pixels along the contour of the image, while the non-square pixel effect was calibrated. Because the resolution was poor in small flocs, data obtained from the small ones (*e.g.* mostly < 100 µm area-equivalent diameter) were inaccurate in that the greatest length was shorter than the area-equivalent diameter. All these incorrect data were excluded from the results. As an example, Fig. 3 shows data obtained from a measurement of one complete photograph, indicating a linear correlation in log-log plots of the area *versus* the greatest length, and of the perimeter *versus* the greatest length, respectively.

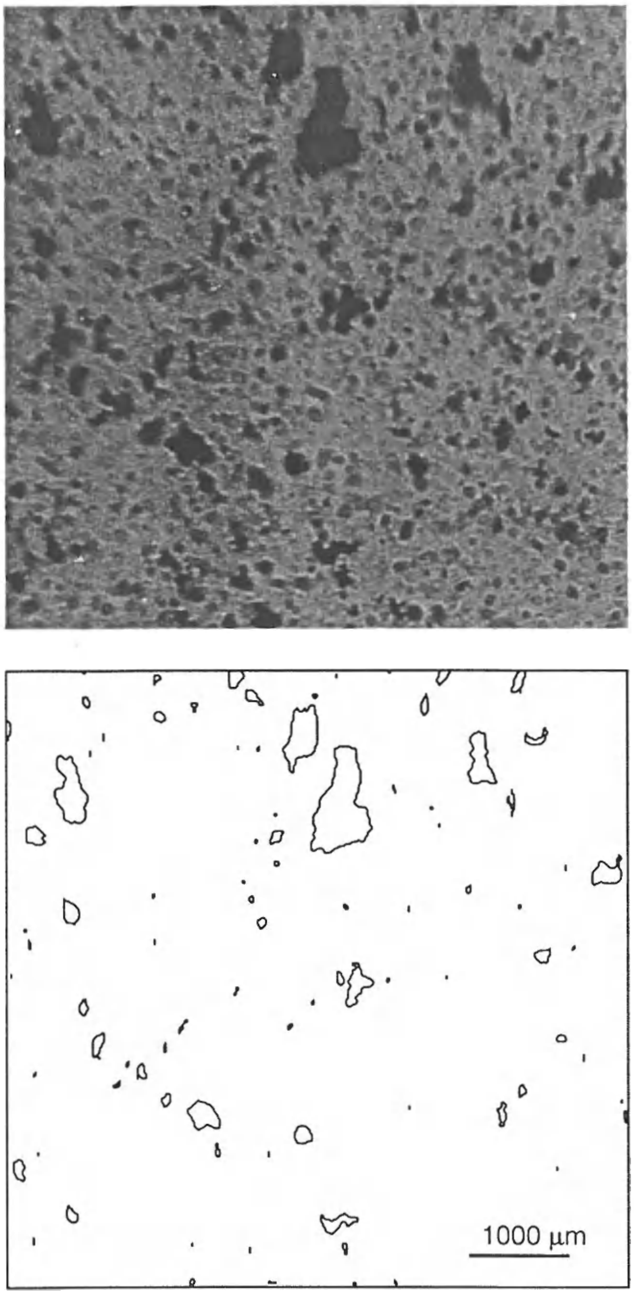

Fig. 2. Part of photograph of flocs (above) taken with the 1:1 underwater camera; sketchy figure (below) illustrates floc images obtained from the photograph and the loss of a number of objects of low contrast after thresholding.

3. RESULTS

3.1. THRESHOLDING EFFECT

The thresholding procedure was crucial to define floc images from the originals in photographs. Although the contrast between photographed flocs and their background was sharp, there were differences in contrast between the flocs. Because of this, it was always a dilemma in thresholding: obtaining reasonably precise images from the flocs of high contrast will result in the loss of those of low contrast, or inclusion of as many images as seen in the photograph will obviously exaggerate the size of those of high contrast. A test of the thresholding effect on D_1, D_2, the number of flocs measured and mean size by number of these flocs was carried out with a photograph by setting a number of the thresholding values between 110 and 190 with steps of 20. For this photograph, a thresholding value of 150 proved reasonable (*i.e.* it produced relatively precise floc images without the exaggeration of those of high contrast). The results show (Fig. 4) that both D_1 and D_2 were changed with the thresholding value irregularly with a standard deviation of 0.03, because the floc images defined changed with the given thresholding value. The number of the flocs decreased as the given thresholding value increased, indicating the loss of floc images

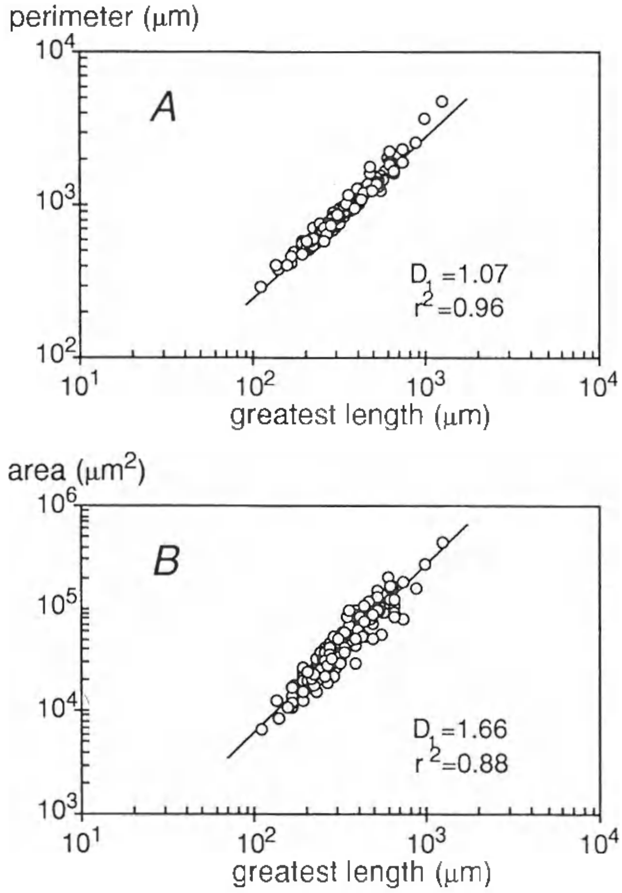

Fig. 3. (A) Linear correlation in log-log plots of perimeter *versus* greatest length for the determination of D_1. (B) Linear correlation of area *versus* greatest length for the determination of D_2.

of low contrast. The increased mean size resulted from the exaggeration of those of high contrast, as the given thresholding value decreased.

3.2. LENGTH SCALE EFFECT

In principle, the dimension of a fractal floc is determined by the configuration of particles within the floc, and is invariant with its size. Since the scaling properties (Eqs 2 and 3) were assumed to determine fractal dimensions of flocs, it is necessary to verify the scaling properties with the range of length scale. Furthermore, the fact that the flocs are composed of various kinds of particle components with their own finite sizes (Chen *et al.*, 1994) also suggests that the values determined in this way may be somehow related to the range of length scale.

To examine the length-scale effect on fractal dimension, a number of different size ranges of data were used to calculate their D_1 and D_2. Each of the size ranges was derived from the same measurement of a photograph, and was selected from a given minimum floc area-equivalent diameter to the same maximum. The results, shown in Fig. 5, indicate that D_2 decreased as the minimum floc size increased (*i.e.* the size range became short) and that D_1 had a peak at the minimum floc size of 406 μm. Both correlation coefficients decreased as the minimum floc size increased, indicating that the scaling properties became poor as the size range became short. The length-scale effect on D_2 seems to suggest that D_2 decreases as the floc size increases. If this is true, it means that the flocs do not exhibit a simple scaling behaviour and that our assumption of the scaling properties is far-fetched. On the other hand, the length-scale effect may also result from the resolution

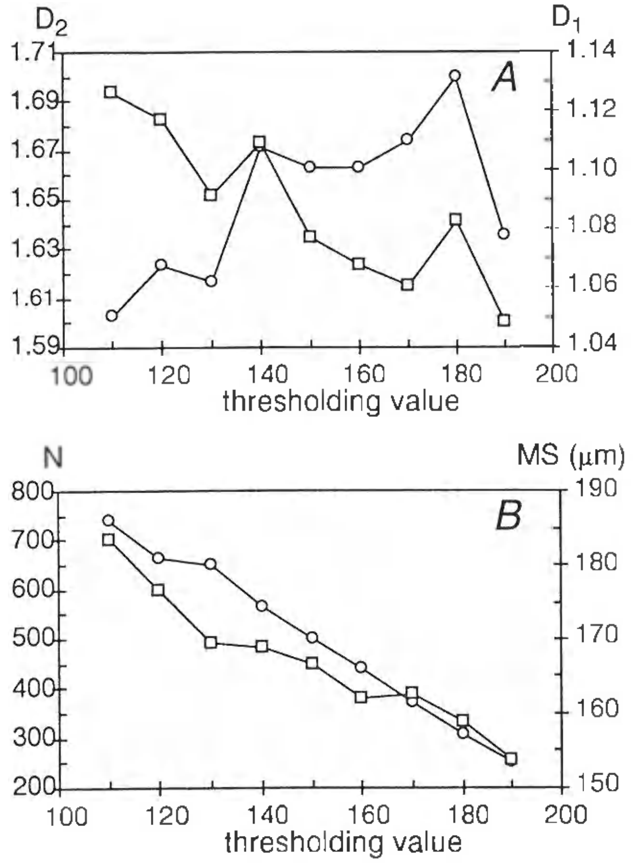

Fig. 4. (A) The change of D_1 (squares) and D_2 (circles) with the thresholding value. (B) Changes of the number of flocs measured (N, circles) and their mean size (squares) with the thresholding value, indicating the loss in floc images of low contrast at high thresholding values, and the size exaggeration of those of high contrast at low thresholding values.

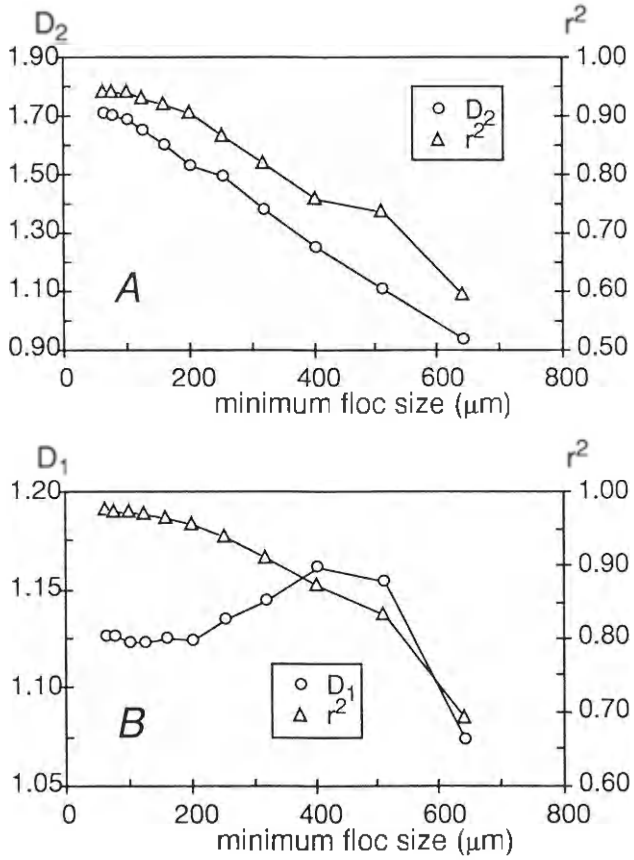

Fig. 5. (top) The decline of D_2 (circles) and of the correlation coefficient (triangles) with increasing minimum floc size. (bottom) The change of D_1 (circles) and of the correlation coefficient (triangles) with increasing minimum floc size.

TABLE 2
Analytical variations in triple measurements of five photographs of one sample (± standard deviation).

photograph no.	*1*	*2*	*3*	*4*	*5*
number of flocs	115±21	42±1	105±5	61±2	47±8
mean size (μm)	150±11	146±3	141±3	153±2	149±5
maximum size (μm)	1530±4	569±5	536±13	554±5	619±8
minimum size (μm)	88±5	108±4	96±4	108±4	111±9
size range (μm)	1441±8	460±8	440±17	445±1	508±4
fractal dimension D_2	1.65±0.05	1.71±0.08	1.68±0.05	1.65±0.03	1.67±0.06
correlation coefficient	0.91±0.01	0.91±0.01	0.82±0.03	0.77±0.01	0.86±0.02
fractal dimension D_1	1.03±0.02	1.00±0.02	1.03±0.02	1.03±0.02	1.05±0.02
correlation coefficient	0.96±0.00	0.94±0.01	0.92±0.01	0.92±0.01	0.94±0.02

in defining floc images because it decreases with the floc size.

3.3. VARIATION IN MEASUREMENTS

Every image analysis of the same one photograph may result in a slightly different set of data. Already a little change in the illumination conditions by variations in the electricity leads to a re-definition of the same images. The position of the boundaries between the sections is determined by the initial position of the photograph (*i.e.* negative) under the microscope. Because this cannot be done exactly the same way in each time, some of the floc images may touch the border at one time of analysis and may not at another. This variation was examined with five photographs of a sample by triple measurements, and the results are given as standard deviations in Table 2. The results indicate that the variation differed among the photographs. The standard deviation for D_1 was around 0.02, and for D_2 was between 0.03 and 0.08.

3.4. FRACTAL DIMENSIONS

The greatest length of the flocs analysed generally ranged from 91 to 2491 μm, with individual samples spanning one and two orders of magnitude. The flocs had fractal scaling properties in one and two dimensions with correlation coefficients above 0.81 (Table 3), and the fractal dimensions were characterized in this way to be between 1.01 and 1.14 for D_1 and between 1.41 and 1.81 for D_2. The details are shown in Table 3, which gives data of the number of measured flocs, mean floc size, size range of measured flocs, fractal dimensions and correlation coefficients of all samples. These values are averages based on data obtained from each photograph of one sample, and standard deviations representing the variation among the photographs. In three of the samples only a few flocs were present in the photographs, so that the values were calculated from data gathered from all photographs of one sample instead of from each of the photographs separately. In this case, a standard deviation for the variation is not given.

TABLE 3
Fractal dimensions for *in situ* flocs in the Elbe estuary and the North Sea and standard deviations for the photograph variation.

sample	*sampling depth*	*number of flocs*	*mean size (μm)*	*size range (μm)*	*dimension D_1*	*correl. r^2*	*dimension D_2*	*correl. r^2*
E1415	surface	472±105	168±5	1157±347	1.09±0.01	0.95	1.68±0.03	0.87
E1530	surface	485±20	130±2	571±50	1.03±0.02	0.90	1.41±0.05	0.81
E1520	bottom	429±22	257±4	2313±268	1.14±0.01	0.97	1.70±0.03	0.95
JCH1	5 m	74±34	148±5	659±438	1.03±0.02	0.94	1.67±0.03	0.85
92WT34	surface	62±13	125±3	744±120	1.04±0.07	0.95	1.61±0.09	0.87
92WT34	bottom	170±26	208±4	1040±102	1.07±0.00	0.96	1.66±0.04	0.88
93SP18*	surface	13	176	302	1.05	0.96	1.81	0.82
93SP18*	bottom	92	163	604	1.01	0.92	1.76	0.84
93SP34*	surface	44	142	347	1.06	0.96	1.81	0.91
93SP34	bottom	406±74	153±2	741±147	1.05±0.01	0.94	1.60±0.05	0.87

* calculated based on data obtained from all the analysed photographs.

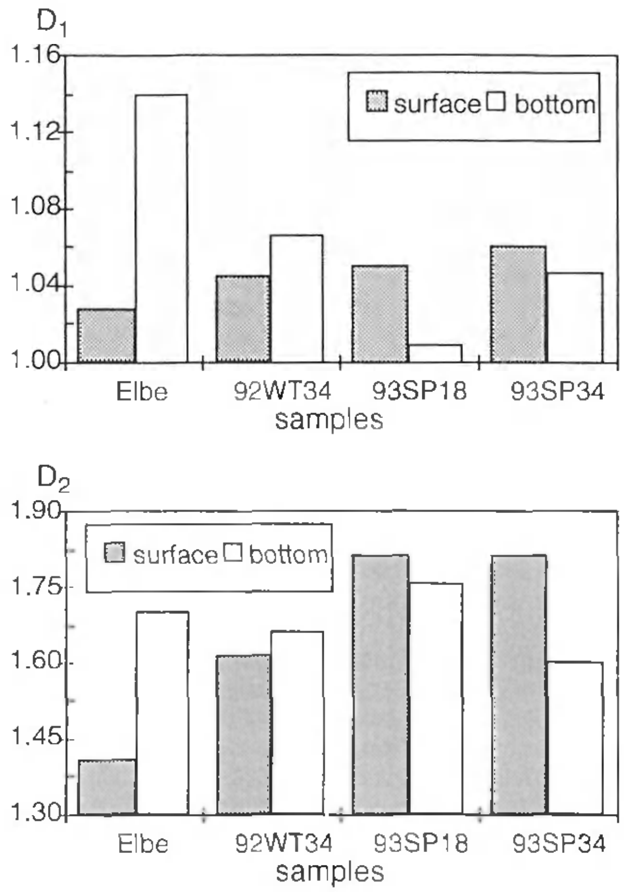

Fig. 6. Comparisons of D_1 (top figure) and D_2 (bottom figure) between the surface (shaded) and bottom (white) samples.

The fractal dimensions may be related to environmental factors. Sampling depth may be such a factor, because of the type of particle aggregation processes (Jiang & Logan, 1991), *i.e.* the possibility to form flocs by the aggregation of fluid shear or differential settling, is affected by water depth. Four pairs of samples were used to compare their D_1 and D_2 values between the surface and bottom waters (samples E1520 and E1530 were taken at 15:20 and 15:30 h, respectively). The results, shown in Fig. 6, indicate no relationship of D_1 or D_2 with sampling depth.

The salinity of water may also be a factor determining fractal dimension. This can be the case for salt flocculation of colloidal particles, in which the salt determines the type of aggregation (*e.g.* DLCA and RLCA) and hence the fractal dimension of flocs (Lin *et al.*, 1989). Fig. 7 shows that the variations of D_1 and D_2 with salinity were irregular. Although salinities were very different between the Elbe water (low) and the North Sea water (high), a relationship of fractal dimensions with salinity could not be observed.

Samples E1415 and E1530 were taken from the surface water at 14:15 and 15:30 h, after high water slack tide. During the period between the two samplings, current velocities increased from 0.06 to 0.85 $m \cdot s^{-1}$ and the water became very turbulent. D_1 and D_2 were higher at low current velocities than at high current velocities (Table 3); the mean floc size indicates that flocs generally became smaller, because of break-up of large flocs at increasing current velocities (Chen *et al.*, 1994).

A relationship of D_1 with the concentration of suspended matter was fairly obvious: the fractal dimension increased with the concentration (Fig. 8). A relationship of D_2 with the concentration, however, was not so good but there appeared to be a slightly decrease of D_2 as the concentration increased (Fig. 8). If the three samples from the Elbe estuary were considered separately, D_2 increased with the concentration, which is opposite to the general relationship.

D_1 and D_2 did not show a relation with the organic content of the suspended matter (Fig. 9), and the correlation coefficients were rather low (< 0.1), whereas the slopes of the regression lines were flat. The three

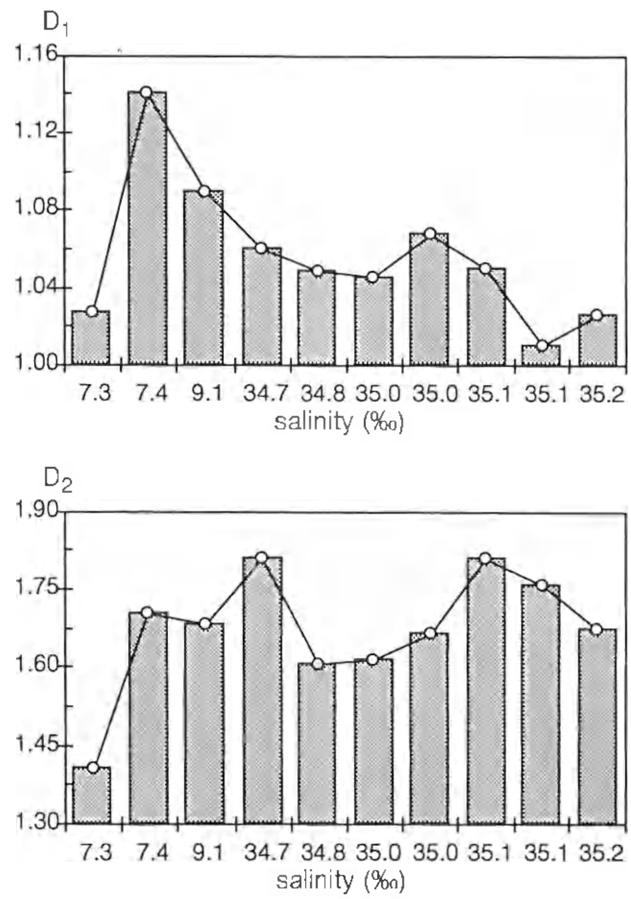

Fig. 7. Variations of D_1 (top figure) and D_2 (bottom figure) with salinity. Low salinities from the Elbe water (7.3 to 9.1 ‰) and high salinities from North Sea water (around 35 ‰).

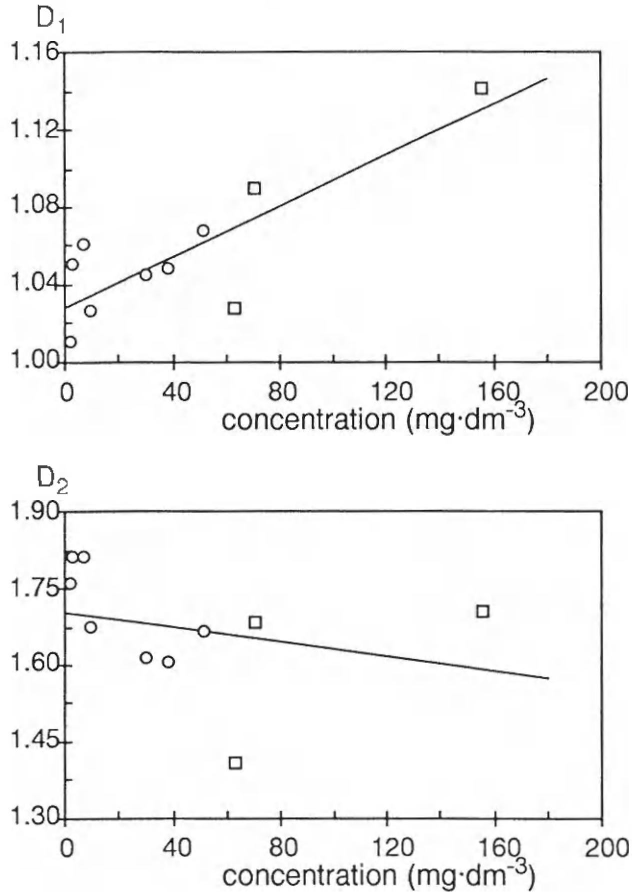

Fig. 8. Relationships between the fractal dimensions D_1 (top) and D_2 (bottom) and the concentration of suspended matter (in $mg \cdot dm^{-1}$). Samples from the Elbe estuary (squares) and from the North Sea (circles).

samples from the Elbe estuary, however, showed an increase of both fractal dimensions with the organic content.

4. DISCUSSION

4.1 ABOUT D_2 AND D_3

In this paper, the first measurements are given of D_1 and D_2 of flocs in estuarine and coastal environments, by use of an *in situ* technique of underwater photography. Fractal dimensions of flocs in aquatic systems have been obtained by Li & Ganczarczyk (1989) and Logan & Wilkinson (1990) using data of the characteristic length and settling velocity (or porosity). Values obtained here for D_2 are the dimensions of projections of *in situ* flocs, or a two-dimensional fractal dimension; therefore, they are not equal to the three-dimensional fractal dimension, D_3, of the flocs, if $D_3 \geq 2$, which is the limit of the method applied here. For flocs with $D_3 < 2$, however, these two-dimensional values can be taken to represent D_3, because for theoretical reasons they are equal (Meakin, 1988).

To take the two-dimensional value as D_3, we must first assume that flocs in our samples had D_3 values < 2. Although the theoretical calculations by Jiang & Logan (1991) indicate some fractal dimensions > 2 for flocs in aquatic systems, Logan & Wilkinson (1990), using experimental data, give values < 2 for D_3 of various kinds of flocs in aquatic systems, except for one oceanic sample with a D_3 of 2.14. This exception may be an overestimate because the data obtained were not based on *in situ* measurements. A fractal dimension obtained from laboratory experimental data may be higher than that from *in situ* data, because floc restructuring may happen during the experiments, which increases the fractal dimension (Lindsay *et al.*, 1987; Meakin, 1988; Logan & Wilkinson, 1990). For example, among all the values for D_3 given by Logan & Wilkinson (1990), the lowest one was obtained from *in situ* data. It is, therefore, reasonable to assume that the flocs in our samples had D_3 values < 2.

Although a D_3 of flocs can be obtained from their projection (if their fractal dimension is < 2), the finite size of the flocs causes a reduction in the dimension of their projection (Nelson *et al.*, 1990). Therefore, the values obtained in this way for D_3 are an apparent fractal dimension in which the true D_3 is underestimated. In an example given by Nelson *et al.* (1990), the difference between the apparent (1.83) and true (1.90) dimensions is not large. It is assumed that for our samples the difference is of the same order.

4.2. EFFECTS ON FRACTAL DIMENSION

Previous studies, including computer simulations and laboratory experiments of various colloids, have demonstrated that the fractal dimension of flocs depends on the type of aggregation kinetics, no matter what kind of particle component the flocs consist of (Meakin, 1988; Lin *et al.*, 1989). Although the knowledge on aggregation kinetics of the formation of flocs in aquatic systems is still lacking, it has been suggested that fractal dimensions of the flocs vary among different environments (*i.e.* reflected by different types of flocs, Logan & Wilkinson, 1990) and vary with the type of aggregation in relation to relative particle motion (Jiang & Logan, 1991).

With respect to relative motion of particles in estuarine and coastal waters, two types of aggregation processes dominate in the formation of flocs studied here: differential settling and fluid shear. According to the aggregation orders of flocs given by Krone (1986), Brownian motion is probably only important for the formation of the first-order flocs during the initial stage of aggregation. Once the flocs grow above a few µm in size, Brownian motion will no longer influence the aggregation process. In the Elbe estuary and the North Sea, more than 90% of volume concentration of suspended matter is composed of particles/flocs larger than 4 μm, as determined by Coulter counter (Chen *et al.*, 1994; unpublished data from the North Sea). It has been hypothesized that these particles/flocs are the basic units composing the larger flocs studied here. Although particles/flocs smaller than 4 μm, as measured by a Coulter counter, make up a very high proportion (> 95% by number) in suspended matter in our study areas, Brownian motion can therefore be regarded as insignificant for the formation of large flocs studied here.

The type of aggregation process in estuarine and coastal waters is strongly affected by environmental factors, such as water depth and tidal current. The aggregation through differential settling is considered to be dominant during slack tide (Eisma & Li, 1993; Chen *et al.*, 1994; Ten Brinke, 1994), whereas fluid shear is significant during high current velocities (Schröder & Siedler, 1989) and declines strongly with the height above sediment bed (Nakagawa & Nezu, 1975). Therefore, a relative strength of the shear at our samples can be assumed by comparing water depth and current velocity data, although measurements of fluid shear were not carried out in this study. A comparison of four pairs of samples collected in surface and bottom waters indicates that the fractal dimensions have no relationship with the water depths (Fig. 6). Comparison of samples E1520 and E1530, and E1415 and E1520, respectively, from the Elbe estuary does not suggest a relationship of the fractal dimension with shear (Tables 1 and 3). Thus the fractal dimension is not related to the type of aggregation process in relation to particle relative motion, although this was stated in a theoretical study by Jiang & Logan (1991).

Salinity probably has little effect on the fractal dimensions of flocs in estuarine and coastal waters. As an example of salt flocculation of colloidal silica given by Lin *et al.* (1989), DLCA and RLCA were carried out with NaCl concentrations of 1.7 and 0.6 M, respectively. In these cases, the salt concentration was a crucial factor controlling the aggregation rate and hence determining the fractal dimension of the flocs. For the flocs studied here, however, salinity is unlikely to play an important role in controlling the aggregation rate: the electrically repulsive barrier between particles while they approach each other is probably not significantly decreased within the salinity range of our samples (S=7 to 35). Hunter (1983) measured electrophoretic mobilities of suspended particles in the Taieri estuary, New Zealand: the values decrease steeply as salinity increases up to S=5, but hardly change as salinity further increases. A similar result from suspended particles (> 1 μm in size) has also been found in the Changjiang estuary (unpublished data). Neither has a clear indication of salt flocculation been found in five western European estuaries (Eisma *et al.*, 1991a). Salt flocculation may take place at the contact between fresh and seawater (Gibbs *et al.*, 1989), but this may not be the case in the low reaches of estuaries and in coastal waters. Flocculation in our study areas is more likely to happen because of the presence of long-chained organic compounds as coatings on the suspended particles composing the flocs (Gregory, 1987; Eisma *et al.*, 1991b). Salinity, therefore, is not a factor affecting the fractal dimensions of the flocs studied here. In fact, our results do not indicate a relationship of the fractal dimension with salinity (Fig. 7).

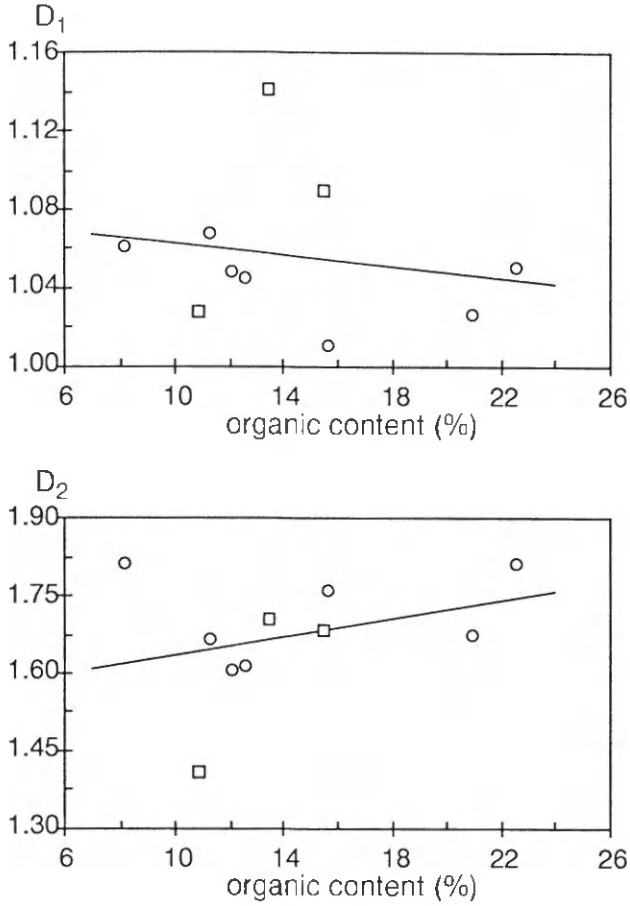

Fig. 9. Relationships between the fractal dimensions D_1 (top) and D_2 (bottom) and the organic content of suspended matter (in %). Samples from the Elbe estuary (squares) and from the North Sea (circles).

The results show that the fractal dimensions vary with the concentration of suspended matter and with its organic content, although the relationships are rather poor (except one between D_1 and the concentration). The reason for the organic content affecting the fractal dimensions is possibly that the cohesiveness of particles composing the flocs is a factor affecting the aggregation rate and hence the structure of flocs. But this is uncertain in this study, since the cohesiveness of particles has not been determined. The relationship of D_1 with the concentration is relatively convincing and indicates that the edge of projection of the flocs is rougher at high than at low concentrations. The flocs with a rough edge are probably those in a cluster-cluster form and these occur more at high than at low concentrations. Although this form of floc can easily break up in strongly turbulent water, the formation rate of such flocs is probably greatly increased by the concentration. The concentration, then, becomes a more dominant factor than fluid motion.

5. CONCLUSIONS

-1. The one- and two-dimensional fractal dimensions of *in situ* flocs in estuarine and coastal waters have been estimated by using image analysis of photographs. The values for D_2 can represent the three-dimensional fractal dimension of the flocs, if $D_3 < 2$. Values obtained in this way for D_3, however, represent apparent dimensions which are slight underestimates of the true dimensions.

-2. Flocs in the Elbe estuary and the North Sea have D_1 values in the range of 1.03 to 1.14 and D_2 values in the range of 1.41 to 1.81. In general, the estuarine flocs are more fractal than the coastal ones.

-3. The results suggest that the fractal dimensions vary among the samples. No relation was found between fractal dimension and fluid shear. Also a salinity effect on the fractal dimension could not be demonstrated. The relation of D_1 with the particle concentration was fairly convincing and suggests that the flocs had a rougher edge of projection at high than at low concentrations. This is possibly because a cluster-cluster form of flocs occurs more at higher concentrations.

Acknowledgements.—The authors are grateful to two reviewers for their helpful remarks on the initial manuscript.

6. REFERENCES

Chen, S., D. Eisma & J. Kalf, 1994. *In situ* size distribution of suspended matter during the tidal cycle in the Elbe estuary.—Neth. J. Sea Res. **32:** 37-48.

Eisma, D., T. Schuhmacher, H. Boekel, J. van Heerwaarden, H. Franken, M. Laan, A. Vaars, F. Eijgenraam & J. Kalf, 1990. A camera and image-analysis system for *in situ* observation of flocs in natural waters.—Neth. J. Sea Res. **27:** 43-56.

Eisma, D., P. Bernard, G.C. Cadée, V. Ittekkot, J. Kalf, R. Laane, J.M. Martin, W.G. Mook, A. van Put & T. Schuhmacher, 1991a. Suspended-matter particle size in some west-European estuaries. Part I: Particle-size distribution.—Neth. J. Sea Res. **28:** 193-214.

——, 1991b. Suspended-matter particle size in some west-European estuaries. Part II: A review on floc formation and break-up.—Neth. J. Sea Res. **28:** 215-220.

Eisma, D. & A. Li, 1993. Changes in suspended matter floc size during the tidal cycle in the Dollard estuary.—Neth. J. Sea Res. **31:** 107-117.

Gibbs, R.J., D.M. Tshudy, L. Konwar & J.-M. Martin, 1989. Coagulation and transport of sediments in the Gironde Estuary.—Sedimentology **36:** 987-999.

Gregory, J., 1987. Flocculation by polymers and polyelectrolytes. In: Th.F. Tadros. Solid/liquid dispersions. Academic Press, London: 163-181.

Hunter, K.A., 1983. On the estuarine mixing of dissolved substances in relation to colloid stability and surface properties.—Geochim. Cosmochim. Acta **47:** 567-473.

Jiang, Q. & B.E. Logan, 1991. Fractal dimensions of aggregates determined from steady-state size distributions.—Environ. Sci. Technol. **25:** 2031-2038.

Krone, R.B., 1986. The significance of aggregate properties to transport processes. In: A.J. Melta. Estuarine cohesive sediment dynamics. Springer-Verlag, Berlin: 68-84.

Li, D. & J. Ganczarczyk, 1989. Fractal geometry of particle aggregates generated in water and wastewater treatment processes.—Environ. Sci. Technol. **23:** 1385-1389.

Lin, M.Y., H.M. Lindsay, D.A. Weitz, R.C. Ball, R. Klein & P. Meakin, 1989. Universality in colloid aggregation.—Nature **339:** 360-362.

Logan, B.E. & D.B. Wilkinson, 1990. Fractal geometry of marine snow and other biological aggregates.—Limnol. Oceanogr. **35:** 130-136.

Lindsay, N.M., M.Y. Lin, D.A. Weitz, P. Sheng, Z. Chen, R. Klein & P. Meakin, 1987. Properties of fractal colloid aggregates. Faraday Discuss.—Chem. Soc. **83:** 153-165.

Meakin, P., 1988. Fractal aggregates.—Adv. Colloid Interface Sci. **28:** 249-331.

——, 1991. Fractal aggregates in geophysics.—Rew. Geophysics **29:** 317-354.

Nakagawa, H. & I. Nezu, 1975. Turbulence of open channel flow over smooth and rough beds.—Proc. Jpn. Soc. Civ. Eng. **241:** 155-168.

Nelson, J.A., R.J. Crookes & S. Simons, 1990. On obtaining the fractal dimension of a 3D cluster from its projection on a plane—application to smoke agglomerates.—Appl. Phys. **23:** 465-468.

Schröder, M. & G. Siedler, 1989. Turbulent momentum and salt transport in the mixing zone of the Elbe estuary.—Est. Coast. Shelf Sci. **28:** 615-638.

Ten Brinke, W.B.M., 1994. *In situ* aggregate size and settling velocity in the Oosterschelde tidal basin (The Netherlands).—Neth. J. Sea Res. **32:** 23-35.

(accepted 3 January1995)