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Factors influencing subaqueous dunes in the Scheldt Estuary

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Abstract The size (wavelength and height) and the factors influencing the characteristics of subaqueous dunes in the river Scheldt between Antwerp and the Belgian-Dutch border were studied. More than 60 dune clusters (each cluster represented by a mean height and wavelength of mostly 10 to 20 or more observations) were analysed. A very good exponential correlation between dune height and wavelength was observed (r = 0.90) which can be described by $H_{\mathrm{mean}} = 0.0321L^{0.918}$. Length/depth ratios vary between 0.2 and 9, height/depth ratios between 0.25 and 0.01. There was no clear relationship between current velocity and dune size, as dunes of various sizes co-exist at the same current velocities. Twenty-two dunes were sampled and show grain sizes (d50) ranging between 0.1 and 0.7 mm. Seven out of eight large scale dune fields were found in sandy and/or hard bottom (gravel, coarse sand and shell fragments) environments, whereas small and medium dunes were found in muddy sand and sandy mud environments.

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Introduction

Subaqueous dunes

The bottom morphology of an estuary is directly related to the sediment dynamics and thus yields complementary information for the evaluation of the sediment budget and resuspension dynamics. For these and other reasons, flow-transverse bedforms have remained the subject of extensive research (e.g. Flemming 1988; Ashley 1990; Harbor 1998; Carling 1999). The research includes both experiments under controlled conditions and observations in natural flows. In the case of the latter, all the observations made should be considered as site-specific measurements and thus do not automatically corroborate the experimental findings (e.g. Gabel 1993).

In the past, little attention has been given to bedform occurrences in the Belgian part of the Scheldt Estuary (e.g. Wartel 1974; Vanwesenbeeck 2000). It is the aim of the present study to describe the geometric characteristics of the subaqueous flow-transverse bedforms of the Scheldt River and to elucidate the factors influencing their size. This includes the relationship between height and wavelength, and the role of water depth, grain size and current velocity or shear stress (e.g. Allen 1968a; Flemming 1978; Rubin and McCulloch 1980; Ashley 1990; Carling 1999). In this site-specific study, an examination of the subaqueous flow-transverse bedforms was performed as part of a general bottom mapping of the Scheldt River between Antwerp and the Belgian-Dutch border (Wartel et al. 2000).

The Scheldt Estuary

The Scheldt River (Fig. 1) is characterised by an average annual discharge of 107 $m^3 s^{-1}$ (average for 1949–1998 at Schelle, Taverniers 1999). Its drainage basin covers an area of almost 22,000 km^2 and is located in the

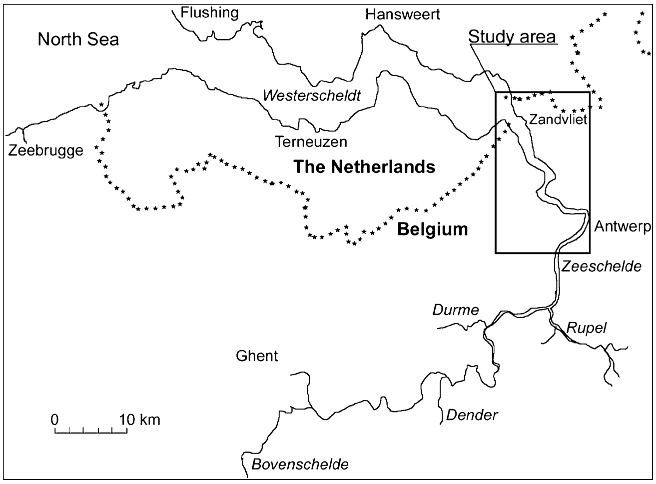


Fig. 1 North section of the Scheldt River basin and location of the study area

northeast of France, the west of Belgium and the southwest of The Netherlands. The tidal regime is semi-diurnal and the tidal wave reaches 160 km upstream at Gentbrugge where it is stopped by a sluice. The mean tidal range reaches 3.8 m in Flushing, 5.2 m in Antwerp and 1.9 m in Gentbrugge (Smets 1996). Upstream from the Belgian-Dutch border (Zandvliet) up to the mouth of the Rupel River (Fig. 1), maximum current velocities occur during flood, reaching up to 1.6 m s^{-1} during an average tide and 2.0 m s^{-1} during spring tide. During ebb, current velocities reach 1.3 m s^{-1} and 1.7 m s^{-1} for an average tide and spring tide, respectively. The bed of the lower part of the Scheldt River downstream of Zandvliet, which is called the Westerscheldt, consists mainly of fine sand (Van Eck 1997). Upstream of Zandvliet sand, clay, and mixed sand/mud bottoms can be found. The deeper parts of the channel consist mainly of erosion-resistant bottoms with gravel and shell fragments. The different lithologies of the riverbed generate a variety of morphological structures such as subaqueous dunes, small cliffs, slumps and structureless bottoms (Wartel et al. 2000; Figs. 2 and 3).

Materials and methods

The survey was conducted on board of the research vessel "VEREMANS" of the Division Maritime Scheldt (Ministry of Flanders), in the period 5 August to 9 September 1999. The bottom morphology was mapped with a C-MAX CM800 side-scan sonar and towfish system. The towfish was kept between 3 and 5 m below the water surface and operated at a frequency of 325 kHz and a horizontal range of 150 m. The flow-transverse bedforms were characterised using an ATLAS DESO 22 single-beam echo sounder, operating at a frequency of 33 kHz. The vertical resolution for this sounder is about 10 cm (ATLAS DESO 22 Datasheet at http://www.osirisnl.com). Positions were recorded using a SERCEL NR103 DGPS system generating a position log on a computer at time intervals of 600 ms.

Sediment samples were collected by means of Shipek and Van Veen grab samplers. Pre-treatment of the samples consisted of sequentially removing organic matter and calcium carbonate by means of hydrogen peroxide and hydrogen chloride respectively. A grain size spectrum was obtained by dry sieving at 1/4 phi intervals between 2,000 and 76 μm, and by analysing the 76 to 2 μm fraction at 1/4 phi intervals by means of an automated Micromeritics Sedigraph 5100 (Wartel et al. 1995).

Current velocities are derived from cubature calculations of the Scheldt Estuary for an average tidal cycle, typical for the year 1980, based on tidal height measurements from a network of 19 stations along the Scheldt River (Smets 1996). Consequently, (maximum) current velocities represent mean values for a total section.

As engineers, physical geographers, geologists, oceanographers and sedimentologists use several systems to classify bedforms, the terminology has become confusing. The nomenclature of the subaqueous flow-transverse bedforms examined in this study is based on the classification proposed at the 1987 Mid-Year Meeting of SEPM in Austin, Texas (Ashley 1990; Table 1). The present work will be restricted to the range of subaqueous dunes, because ripples are too small to be visualised and measured by the equipment used.

Results

Wherever the records of the side-scan sonar and the echo sounder gave a clear view of the dunes (Figs. 4 and 5), their parameters (height and wavelength) were measured. Dunes of similar height and length tended to occur in clusters, in which case all observations within such a group are represented by the mean heights and lengths, resulting in a data set of 61 clusters. The clusters can be found throughout the study area (Wartel et al. 2000; Fig. 3) and are characterised by an average length and width of 170 and 85 m, respectively. In one case, medium dunes were superimposed on large dunes; here the dune field was split into two sub-clusters, each with its respective average height and wavelength.

The dunes in the river Scheldt exhibit an exponential relationship between their height and their wavelength which can be described by the equation $H_{\mathrm{mean}}=0.0321L^{0.9179}$ ($r=0.90$, $n=61$) as displayed in the linear log/log plot of Fig. 6. The relationship lies slightly below and has a somewhat higher slope compared to that of the global data set published by Flemming (1988, 2000b), as can be seen in the linear log/log plot of Fig. 7. The higher exponent may in part be due to the fact that the present study is site-specific. As can be seen in Fig. 7, it is not unusual that individual trends depart from the global trend which can be considered as an equilibrium condition.

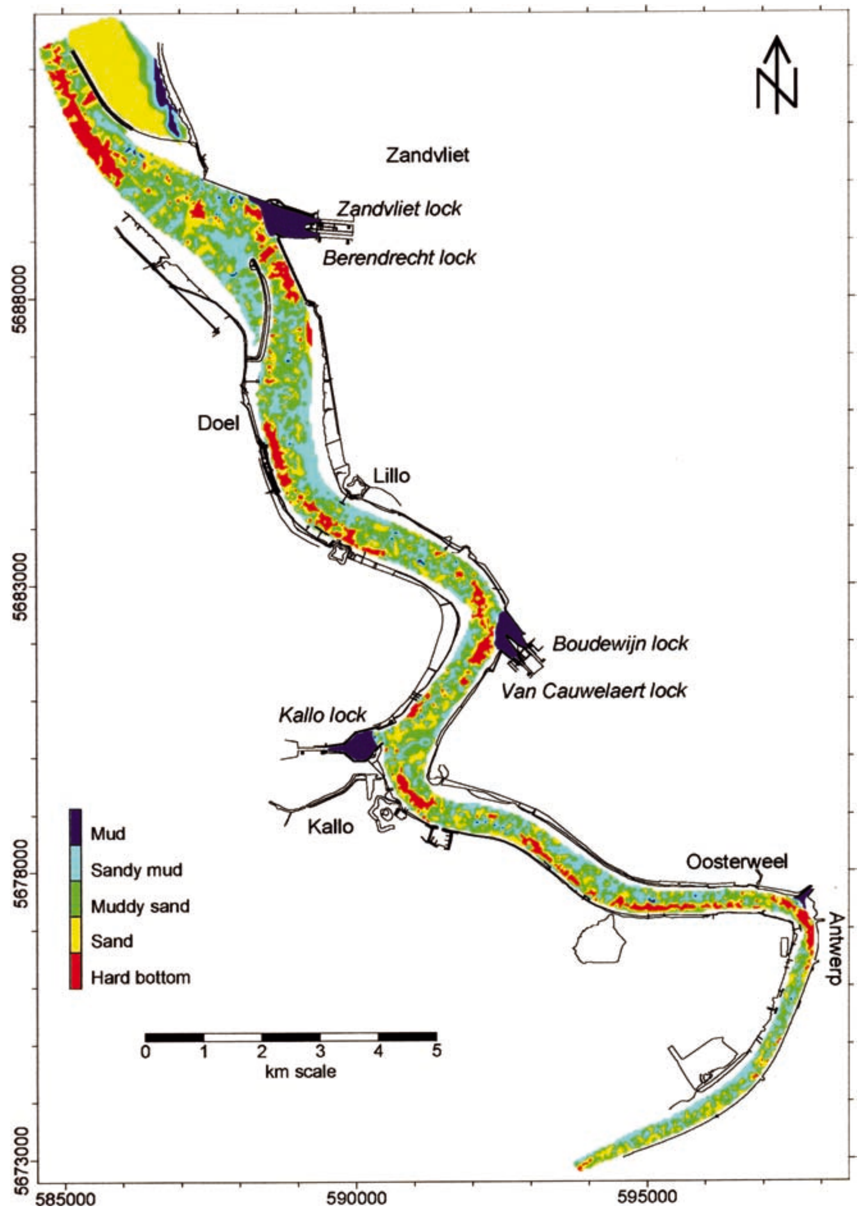
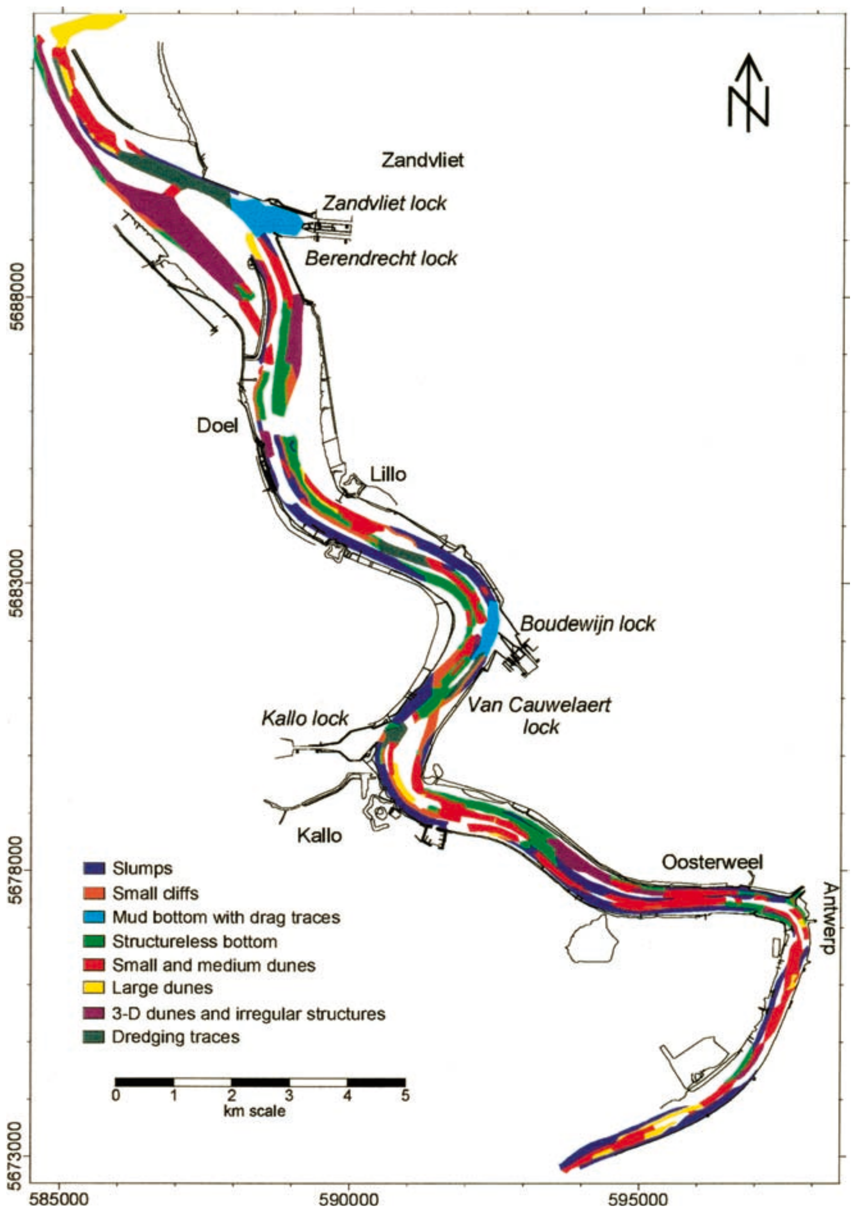


Fig. 2 Lithological map of the river Scheldt between Antwerp and the Belgian-Dutch border. Lithological fractions are split into five categories: mud (*blue*), sandy mud (*light blue*), muddy sand (*green*), sand (*yellow*) and hard bottom (i.e. gravel – *red*) (after Wartel et al. 2000)

The Scheldt River bedforms lack a good correlation between flow parameters, such as depth and velocity, and their dimensions. Length/depth ratios vary between 0.2 and 9, whereas height/depth ratios lie between 0.25 and 0.01 (Figs. 8 and 9). The upper ratio boundaries, $L/d \approx 9$ and $H/d \approx 1/4$, respectively, may reflect the maximum sizes dunes can attain. The largest dunes in Fig. 6 indeed reflect equilibrium conditions. Furthermore, the Scheldt River dunes also do not exhibit a clear relationship between their dimensions and the current velocity for the complete data set ($n=61$, $r^2=0.008$ – current velocity data from Smets 1996), as dunes of various sizes co-exist at the same current velocities. However, one would not expect all dunes to respond in the same manner to the current velocity when dunes are composed of different sediment types. Indeed, for a given cross section of the study area the bed seems to be heterogeneous in sediment composition (Fig. 2)

Some of the bottom samples collected during the general survey for the lithological map of the area were recovered from the dune bodies investigated in this paper. Such samples could hence be used to study the relationship between dune morphology and grain size. Figure 10 shows the maximum dune height derived from a known length plotted against the median diameter (d50) of the sand fraction (> 63 μm). Included is also the apparently well-defined upper limit of dune height for a given grain size observed by Flemming (1988, 2000b) along the southeast African continental margin. The Scheldt River data presented in Fig. 10 seem to lie more or less under this upper limit although we cannot neglect the fact that the clay and silt fraction were not taken into account. For the dunes presented, sand contents range from 20 to 100%, and clay contents from 0 to 33%. Echo sounder traces of these dunes show that some of them display rounded crests, probably indicating that

Fig. 3 Morphological map of the river Scheldt between Antwerp and the Belgian-Dutch border. The following structures were identified: slumps (*blue*), small cliffs (*orange*), mud bottom with drag traces (*light blue*), structureless bottom (*light green*), small and medium subaqueous dunes (*red*), large dunes (*yellow*), three-dimensional dunes and irregular structures (*purple*), dredging traces (*green*) (after Wartel et al. 2000)



they had been inactive for some time. They may hence have been draped by finer sediment at the time of sampling, explaining the larger fine fraction (Fig. 4).

Discussion

Several authors have observed a positive exponential relationship between the dune heights and their wavelengths (e.g. Allen 1968a, 1968b; Terwindt 1971; Flemming 1978). The most extensive compilation of dune data has been presented by Flemming (1988, cf. also Ashley 1990), featuring data from flume studies and natural systems (e.g. tidal current-dominated shelf areas, estuaries, and rivers). For this data set ($n = 1491$), the author obtained a high degree of correlation ($r = 0.98$), resulting in the relationship $H_{mean} = 0.0677L^{0.8098}$. An

Table 1 Classification of subaqueous dunes (Ashley 1990)

	Ripples	Dunes			
		Small	Medium	Large	Very large
Wavelength (m)	< 0.6	0.6–5	5–10	10–100	> 100
Height (m)	< 0.075	0.075–0.4	0.4–0.75	0.75–5	> 5

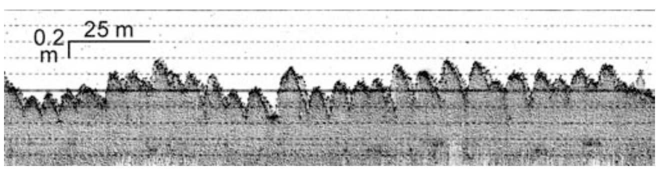


Fig. 4 Echogram showing small and medium sized dunes (each major division is 1 m, each small division is 0.2 m)

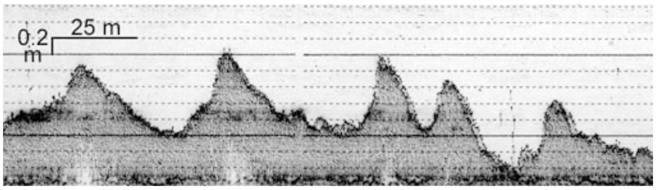


Fig. 5 Echogram showing large dunes (each major division is 1 m, each small division is 0.2 m)

apparent upper limit in dune height versus wavelength was also observed, which followed the relationship $H_{\max} = 0.16L^{0.84}$. The somewhat higher slope in the relationship between dune height and dune length in the present study may be due to a time lag in the response to individual tidal cycles which could affect small dunes more than large dunes, the latter probably being controlled by the spring-tide cycle. Also, from the height versus length relationship one can deduce that the wavelength of dunes grows faster than their height (see Fig. 7). For larger dunes, the amount of sediment needed to obtain equilibrium between the length and height can become a limiting factor (Flemming 1988). On the other hand, the trend groups well with the other trends presented in Fig. 7, suggesting site-specific effects.

Subaqueous bedforms can be divided into two groups: those in which length is independent of water depth (ripples in case of flow-transverse bedforms), and those in which length correlates with water depth (e.g. subaqueous dunes; Allen 1968b; Yalin 1972). Allen (1968b) proposed an exponential relationship between the length of dunes and water depth in which $L = 1.66d^{1.55}$. Other studies (e.g. Lane and Eden 1940; Jordan 1962; Flemming 1978; Terwindt and Brouwer 1986) have reported data that indicate that this relationship should not be generalised. Rubin and McCulloch

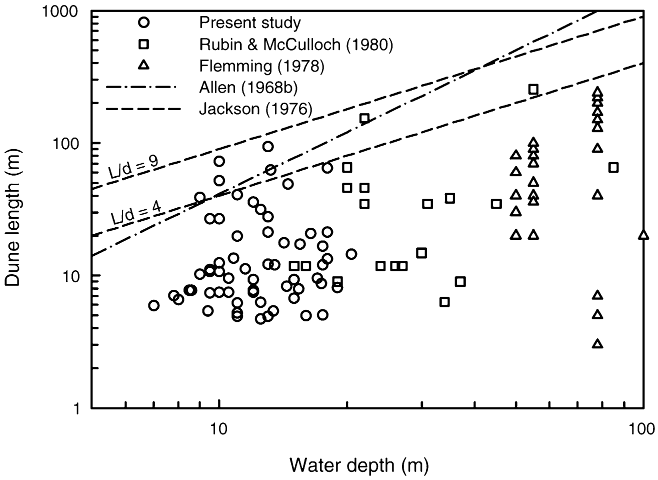


Fig. 8 Relationship between dune length and water depth: present study compared to published data sets

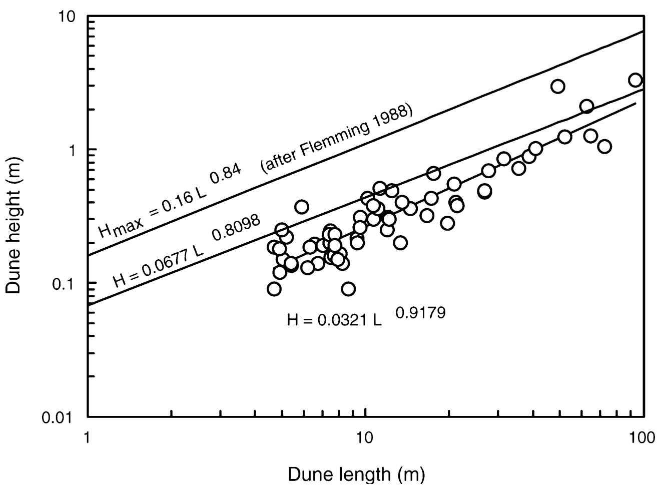


Fig. 6 Relationship between dune height and dune length: data from present study compared to data from Flemming (1988)

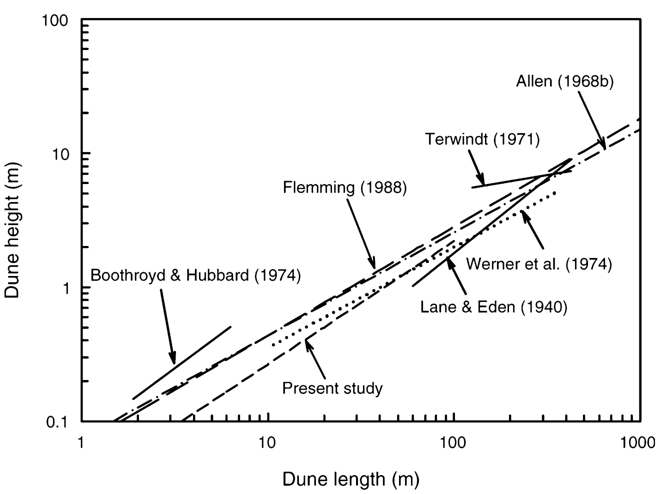


Fig. 7 Dune height versus dune length: mean trends for the present study and a selection of published data sets

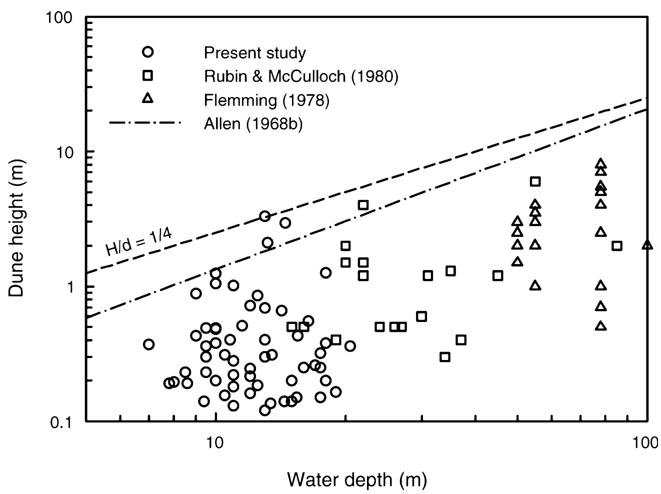


Fig. 9 Relationship between dune height and water depth: present study compared to published data sets

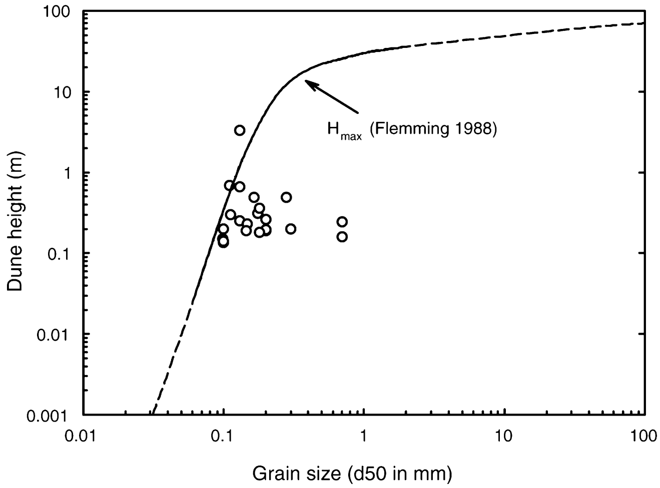


Fig. 10 Dune height versus grain size, together with maximum dune height as a function of median grain size (after Flemming 1988)

(1980) showed that the dune height was less or equal to 1/6 of the mean flow depth. They also stated that the dune height and water depth did not reach the maximum ratio when current velocity and grain size were less than optimal, indicating that depth is not the only controlling parameter. Bridge and Jarvis (1982) found poor correlations between dune height or length and depth, their data producing excessive scatter. In the present study, as can be seen in Fig. 8, length/depth ratios varied strongly, without any clear inter-relationship. When comparing our data with those of Rubin and McCulloch (1980) from San Francisco Bay and Flemming (1978) from the southeast African continental shelf, it can be seen that the upper boundary of the dune length shifts upwards with water depth. The wavelength seems to be limited roughly to about 9 times the depth of the water column ($L/d \approx 9$), indicating that dune height increases with increasing water depth in various flow systems (from shallow and small to deep and large: the Scheldt Estuary, San Francisco Bay and the African continental shelf). Together with depth, the total water mass flowing through these three environments increases. The width of the environment, a measure of the water mass flowing through it, is limited to a few hundred meters in the present study area, whereas it is 1.5 to 20 km in the San Francisco Bay and over 20 km on the southern African continental shelf. In the case of the dune height, the relationship to water depth and water mass becomes even clearer. Here all data of dune heights presented (Fig. 9) are limited to 0.25 times the water depth ($H/d \approx 1/4$). This limit is also supported by the data of Terwindt (1971). A linear relationship between water depth and dune height or wavelength would suggest a dependency of the dune height on the water depth. In combination with other published data, the present observations indeed indicate a dependency of maximum dune size on water depth. The large scatter, however, suggests that this feature is not the only limiting factor for dune size.

Flows which exceed the threshold of grain motion will deform an initially flat bed into various types of bed features, including flow-transverse dunes. Increasing the current velocity over a dune will increase the shear velocity, and consequently the shear stress in the boundary layer above the dune. McCave (1971) studied dunes in the North Sea and the relationship between dune height (H), dune length (L), water depth (d), critical mean velocity ($\bar{U}\bar{U}_c$) and ratio (B) between the rate of transport of material in bed-form propagation (T_b) and the total sediment transport rate (T_t). The author modified Kennedy's (1969) earlier equation into $H=(LB/n)((\bar{U}\bar{U}_c)/\bar{U})\tanh(2d/L)$ where n is a constant, demonstrating that an increase in velocity produces an increase in dune height, until suspended sediment transport becomes large relative to the bedload transport rate (diminishing the value of B), causing a decrease in dune height. At even higher current velocities the dunes become washed out, and the bed becomes flat while sediment transport takes place as a slurry or sheet flow a few millimeters thick above the bed. This phenomenon occurs when the criterion, $\tau_{os} > 0.8g\rho(s-1)d$, is approximately fulfilled (Soulsby 1997), where τ_{os} is the skin-friction bed shear-stress, g the acceleration due to gravity, ρ the water density, s the relative density of the sediment and d the grain diameter. Harbor (1998), however, did not find a clear relationship between the current velocity and the dune height in the Mississippi River. He only found one particular site where dunes grew with increasing velocity, producing an order-of-magnitude scatter. Terwindt and Brouwer (1986) observed a low correlation between the current velocity and dune dimensions on an intertidal shoal in the Westerscheldt. In the present study area, there is no clear inter-relationship between the ratio of dune height to dune length (H/L) and the maximum current velocity (V_{max}). As a range of grain sizes is present dunes probably will respond in a different way to the current velocity, fine-grained dunes having a smaller equilibrium size than coarse-grained dunes (Fig. 10). The finding that small dunes occur throughout the study area, together with higher hierarchies, favours the amalgamation process for dune growth (Flemming 2000a).

Water depth will limit further dune growth once the current velocity above the dune crest exceeds a grain size-dependent critical shear velocity (Soulsby 1997; Flemming 2000b), indicating that dune size is indeed grain size dependent. Simons et al. (1965), McCave (1971) and Rubin and McCulloch (1980), amongst others, observed an increase in dune height with increasing sediment size. Carling (1999), however, showed that for coarse sediments (sand-gravel), grain size does not have a discernible effect on the size of the dunes. Figure 10 illustrates that for the sampled dunes median grain sizes range between 0.1 and 0.7 mm (fraction >63 μm). When the fine fraction is included, the median grain size shifts in such a way that some dunes contain grain sizes below 0.1 mm. Possibly, the dunes were covered with a thin layer of fine sediments, indicating changed hydrodynamics because of neap-spring or seasonal variations. The data for the calculation of the maximum dune height (H_{max}) in Fig. 10 consist entirely of dunes sampled on the South African continental shelf (grain sizes from 175 to 700 μm, Flemming, personal communication) and may hence reflect a site-specific relationship. Even so, data from the Scheldt dunes seem to be in agreement with the proposed maximum dune height. Wilcock (1992) reported that sorting has a measurable effect on the size and shape of sandy bedforms, indicating that grain size alone is not enough to predict dune characteristics. The high amount of organic matter in the Scheldt sediments (10 wt% and more; Wartel et al. 2000), which tends to be associated with the finer sediment fraction, may also contribute to a higher degree of cohesiveness. This could result in dunes with a higher threshold value of the skin-friction shear-stress (τ_{os}) at which grain motion starts. Wartel (1974) detected a relationship between the dune height and the mean grain size whereby the ratio varied between 1.5×10^3 and 3.0×10^4 for this part of the river Scheldt. The present study shows a similar variation of the ratio (between 2.3×10^2 and 2.9×10^4), which is also consistent with Allen's (1968b) findings (2.0×10^2 to 1.0×10^5). Also, in the present study seven out of eight large scale dune clusters were found on sandy and/or hard bottoms (gravel, coarse sand and shell fragments), whereas small and medium dunes were also found on sandy mud and muddy sand environments (Wartel et al. 2000).

Conclusions

The dunes in the Scheldt River seem to be influenced in varying degree by a series of factors. These include (i) water depth, (ii) current velocity and (iii) sediment composition. In the case of water depth, the suggestion is made that the scale of the environment, as a measure of the water mass flowing through it, should also be taken into account. Concerning the effect of the current velocity, no clear inter-relationship with dune size was found. The relationship between dune height and grain size is in agreement with the findings of previous investigations in the area (Wartel 1974) and seems to comply with data form the southeast African continental shelf (Flemming 1978). Moreover, the distribution of large dunes seems to be limited to sites with sediments that can be categorised as (coarse) sand, gravel and/or shell fragments.

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