Marine dune morphodynamics and sediment fluxes (off Dunkirk, France). Spatio-temporal variability and relations with hydrodynamic forcings.

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ABSTRACT: In the context of the future wind turbine project off Dunkirk (North of France), the morphodynamics of six medium to very large dunes (water depth around 14.5m LAT; heights around 1-3m; wavelengths around 84-232 m) is investigated. On the basis of eight bathymetric surveys realised between November 2019 and July 2021 (20 months), dune morphometric parameters, migration rates and associated sediment fluxes have been quantified. The spatial (intra- and inter-dune) and temporal variability in dune mophodynamics has been inspected through statistical analysis in relation with meteo-marine forcings. A strong intra-dune and weaker interdune variability is observed in dune morphology (e.g. wavelength, height, width), while dune migration and sediment fluxes display a similar response to forcing modifications. Some recommendations can be drawn up concerning the monitoring of dune fields in offshore wind farms.

1 INTRODUCTION

On the continental shelf, bedforms are mobile morphologies under the action of tides, winds and waves. The installation of offshore wind structures is concerned with major technical challenges, such as scouring around the pile foundations, burying and unearthing of cables (Carter et al., 2014), phenomena which are particularly exacerbated when the sedimentary dynamics is important and when submarine dunes are present (Couldrey et al., 2020). Marine dunes are located on sediment transfer pathways; they constitute essential functional areas for many biological species, and are such classified by the MFSD and Natura 2000 as a determinant habitat. The disturbance of these environments with the installation of seabed man-made structures can have significant consequences and needs to be anticipated and constrained.

Dunes morphodynamics is controlled by many factors such as sediment grain-size and hydrodynamics. It responds to variable meteo-marine forcings (tides, e.g. Tonnon et al., 2007 ; winds, waves, storms, e.g. Campmans et al., 2018) and sediment fluxes with modifications of their morphology and migration rates. However, the variability in dune morphodynamic response at the scale of the dune and the dune field is barely investigated (e.g. Salvatierra et al., 2015).

The objective of the present study is to get insights on dune morphodynamics in the area of the future wind turbine area off Dunkirk, with a special focus on the spatio-temporal variability of dune morphology, migration rates and associated sediment fluxes in response to various meteo-marine conditions.

2 STUDY AREA AND CONTEXT

A 50-km2 600 MW wind turbine project is planned in the southern North Sea, 10 km offshore Dunkirk (Fig. 1). This project aims to install a maximum of 46 wind turbines placed on the Binnen Ratel sandbank, connected to the land by cables passing in between the different coastal sandbanks up to Dunkirk. In order to better understand the burial and unburial of cables, the morphodynamic characteristics of the dunes and the associated sedimentary fluxes were studied within the framework of the DUNES project. The results presented here relate to a field of 6 dunes of around 0.5 km2 located along the cable corridor, in water depths between 14 and 17 m (Fig. 1).

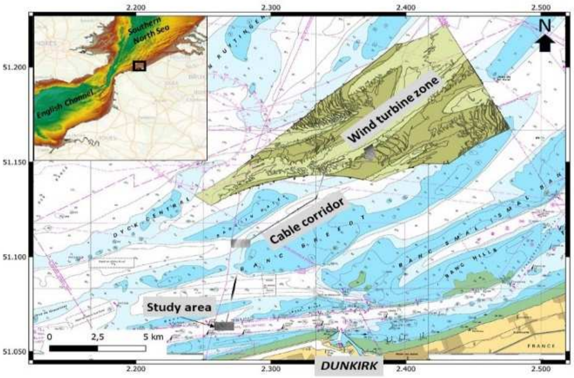

Figure 1. Localisation of the wind turbine project and the study area.

In the study area, the seabed is moulded with Holocene sandbanks, covered with large marine dunes, with heights about the meter and wavelength about the hundred of metres, and composed homogeneously of unimodal slightly gravelly sands with a mean median of 327.8 mm (Robert et al., 2021).

Tides are semi-diurnal with a macrotidal regime (3.5 and 5.5m in mean neap and spring conditions respectively; © SHOM). Flood and ebb currents flow towards the E-NE and W-SW respectively, with velocities mainly between 0.75-1 m/s and 0.5-0.75 m/s (© SHOM).

Residual flow is oriented towards the E-NE. Winds are mainly from SSW-WSW, with a secondary component from N-NE sector. Strong winds (>50 km/h) represent less than 1% of observations. Waves are mainly form SW and NE and attenuate on reaching the subtidal sandbanks with heights not exceeding 1.2 m for periods of 4 to 8 s in 80% of cases (Latapy et al., 2019).

3 MATERIAL AND METHODS

To characterize dune morphodynamics, sedimentary fluxes and their relation with hydrodynamics, bathymetric data as well as tide and wind data have been collected over a 21-month period.

3.1. Bathymetric data to morphodynamic parameters

Eight bathymetric surveys (namely S1 to S8) have been acquired between November 2019-July 2021 by GEOxyz using a Kongsberg EM2040C multibeam echosounder. Data resolution and accuracy are respectively 0.5 m and 0.05 m. A DEM has been produced at a 0.5-m resolution for each date.

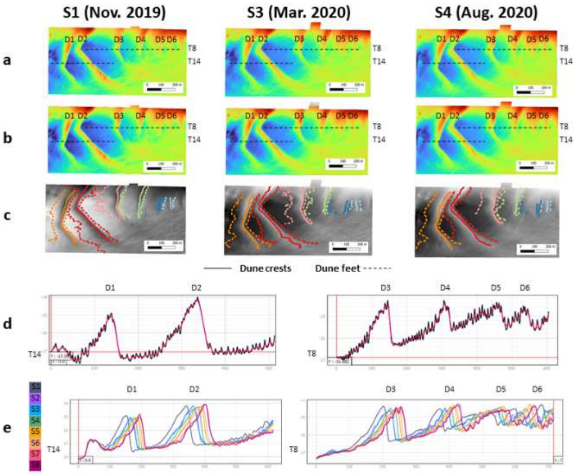

Figure 2. Bathymetric data processing. a: raw DEMs, b: filtered DEMs, c: DODs, d: vertical profiles (T8 and T14) in raw (black) and filtered (red) DEMs for S3, e: Vertical profiles (T8 and T14) in filtered DEMs for all surveys (S1 to S8).

Dunes are covered with smaller superimposed dunes (Fig. 2-a,d). In order to focus on the largest forms, DEMs have been filtered using a spatial low pass filter (Fig. 2-b). Dune crests and feet have been digitized (Fig. 2-c). Morphometric parameters (height, wavelength, width, sinuosity and asymmetry indexes, crest depth) and migration distances of the dune crests have been measured from DEMs using QGIS along 20-m spaced profiles, perpendicular to dunes (West-East oriented) (Fig. 2-e).

3.2. Meteo-marine forcings

Data on meteo-marine forcings have been compiled. Coefficients indicative of tidal ranges (© SHOM) indirectly inform on tidal current strength and have been classified in 4 classes (neap, weak and strong spring, exceptional spring). The SW and NE events of strong winds (>50 km/h) were identified from the hourly data recorded at the Dunkirk meteorological station (infoclimat.fr). For each of the 7 periods in between bathymetric surveys, the meteo-marine have been resumed as follows : (i) percentages of occurrence of each tidal range class, and (ii) the duration and the number of strong wind events from SW and NE sectors.

3.3. Sediment fluxes

Sediment fluxes have been estimated over the 7 time-periods using the “dune tracking” formulation (Schmitt et Mitchell, 2014). This method considers that the sediment volume change of the dune form during the studied period can be related to sediment flux during this period, and is described by following formula:

$$Q_b = C \cdot H \cdot f \cdot (1 - \phi) \qquad (1)$$

where C = dune migration rate; H = dune height; f = dune shape factor; and Φ = sediment porosity (0.4 classically used for sands).

The dune shape factor (*f*) is given by Equation 2:

$$f = \frac{V}{\lambda \cdot H} \qquad (2)$$

where λ = dune wavelength; and V = dune surface (dune assimilated to a rectangular triangle) given by Equation 3:

$$V = (L \cdot H) \,/\, 2 \qquad (3)$$

where L = dune width.

The volumic mass of silica (2650 kg/m^3) is used to express the fluxes in t/m/yr.

A code developed by Blanpain (2009) is used to estimate sediment fluxes with empirical formulas for the S2_S3 time-period where North-East have prevailed. The objective is to: (i) compare the sediment fluxes values obtained from “Dune tracking” method and empirical formulas, and (ii) better understand the reversal of dune migration direction observed during L2-L3 period. The formulas of van Rijn (1984) and Wu et al. (2000) are used in their classical form, and the formula of Yalin (1963) is adapted to include the wave influence:

$$Q_Y = \frac{0{,}5\,.\;U\,.(u_*^2 - u_{cri}^2)}{(s-1)g} \qquad (4)$$

where U = $u_c + u_b$ describe the sum of the bottom current and orbital velocities; u_* = bottom friction, u_{cri} = critical velocity at which the sediment motion is initiated, s = the ratio between water and sediment volumic mass; and g = the gravity acceleration.

The fluxes are estimated at the center of the study area where the water depth is 15.6 m. Bottom current and free-surface elevation hourly timeseries were extracted from a MARS3D simulation while hourly wave conditions were extracted from a WaveWatch III (WWIII) simulation (Boudiere et al., 2013). Following the “Dune Tracking” method, sediment fluxes are expressed in t/m/yr and projected over the West-East axis (the transport direction is considered equal to the current direction).3.4. Statistical analysisStatistical analysis were performed to inspect the spatio-temporal variability of dune morphodynamics.

Statistical analysis was performed using R software (version 4.2.0; R Core Team, 2022) to analyse the spatio-temporal variability of dune morphodynamics. A linear mixed model was considered to investigate the effect of the dune, the survey (i.e. S1 to S8) and their interaction on dune wavelength, by considering a random effect of the transects. The model was fit using the R package lme4 (Bates et al., 2015).

For each dune, the maximum height, the maximum width and the maximum sinuosity among all transects were calculated for each survey. The difference between dunes was tested for these parameters using a non-parametric one-way analysis of variance, since assumptions of normality and homoscedasticity of data were not verified. A post hoc pairwise Wilcoxon rank sum test with Bonferroni correction was then performed to compare differences between pairs of dunes.

STATIS method is a multidimensional factorial analysis adapted for 3D datasets (variables*sites*dates) which cannot be explored by principal component analysis (PCA). It proceeds in three steps which allows us to focus the analysis at different temporal and spatial scales. The interstructure step realizes a classification of 2D tables (variables*samples). The compromise step performes a PCA to all 2D tables weighted by their contribution to the total variance. The intrastructure computes a PCA to every 2D table (variables*sites or dates) and plots the results in the compromise factorial plane to allow us the comparison of all factorial planes (Fournier et al., 2009).

4 RESULTS AND DISCUSSION

4.1. Meteo-marine scenarios

Over the entire study period, 174 wind events greater than 50 km/h and 145 days of cumulative duration of these events were recorded (Fig. 3).

During the 7 periods studied (S1_S2 to S7_S8), the wind conditions were variable (Fig. 3-a). Three scenarios can be distinguished according to the proportion of strong winds coming from the South-West and North-East sectors: 90% of the winds coming from the South-West sector (period S1_S2), 100% of North-East winds (S2_S3, S7_S8), and more variable winds, coming for 55-70% from the South-West and for 30% from the North-East (S3_S4, S4_S5, S5_S6, S6_S7). The periods S1_S2, followed by S4_S5, S6_S7 and S5_S6 periods, display high values of the wind index (number of events x cumulative duration of events) indicating a strong influence of wind conditions. Considering tidal conditions (Fig. 3-b), periods L1_L2, L2_L3, L4_L5 and L6_L7 are concerned with spring conditions for more than 10% of the time period duration (up to 18% for L2_L3).

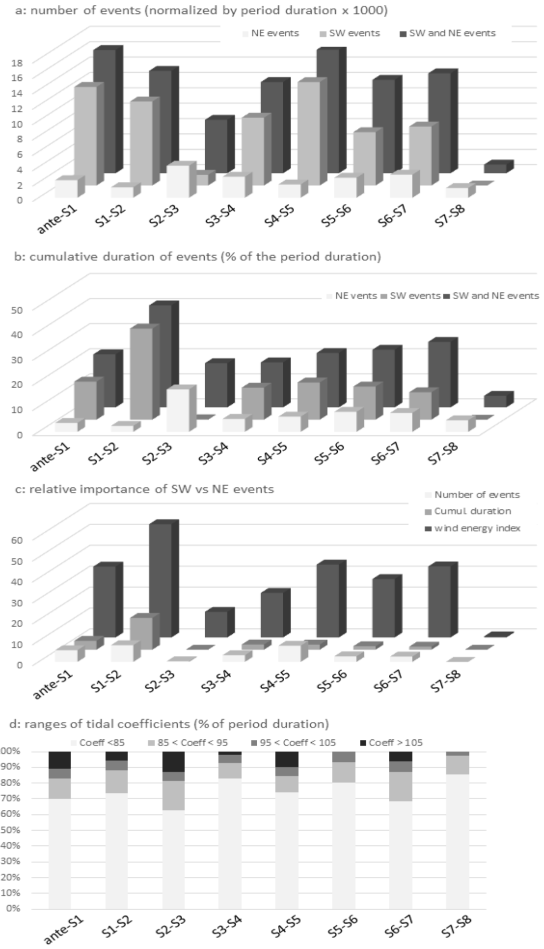

Figure 3. Tide and wind conditions during the 7 studied time-periods (S1_S1 to S7_S8). a: winds from SW and NE sectors per period: number of events, cumulative event duration and wind index (number of events x cumulative duration of events). b: tidal coefficient (>95 for spring tides).

In summary, the periods L1_L2, L4_L5 and L6_L7 display the most energetic hydrodynamic conditions, with preponderant SO winds for L1_L2 but variable wind directions for L4_L5 and L6_L7. The L2_L3 period is concerned with moderate energetic conditions, but winds come exclusively from NE sector.

4.2. Dune morphology

The bedforms observed on the seabed of the stud area are medium to very large dunes, named D1 to D6. They are oriented North-South, perpendicular to tidal currents, with crests around 14.1-14.5 m water depth. Their mean heights and wavelengths are between 1 and 3 m and 84 and 232 m respectively (Table 1). A significant relationship is found between dune height and wavelength (not observed with water depth) displaying a very low mean height/wavelength ratio of 0.012 (0.007 to 0.019) indicating dune equilibrium is not reached probably due to important wave effects and suspension increase (e.g. Ernsten et al., 2006; Tonnon et al., 2007):

$$H = 0{,}0137\lambda^{0{,}9088} \quad (R^2=0{,}66) \qquad (5)$$

Table 1. Dune morphometric parameters, migration rates and associated sediment fluxes (“dune tracking” approach).

Parameters	Symbols	Mean or s.d.	D1	D2	D3	D4	D5	D6
Wavelength	λmean (m)	mean	164,61	216,1	232,92	164,32	120,77	84,65
		s.d.	8,02	6,04	5,76	4,34	4,62	10,16
Height	Hmax (m)	mean	2,96	2,93	2,32	1,45	1,19	1,03
		s.d.	0,08	0,16	0,11	0,13	0,16	0,19
Width	Lmax (m)	mean	241,83	275,96	187,61	169,49	145,16	73,67
		s.d.	80,07	23,18	26,64	9,66	8,06	8,97
Asymmmetry index	Ia	mean	0,32	0,52	0,26	0,22	0,31	0,58
		s.d.	0,03	0,02	0,02	0,04	0,16	0,07
Sinuosity index	Is	mean	0,82	0,77	0,87	0,87	0,88	0,86
		s.d.	0,06	0,05	0,05	0,08	0,05	0,1
Crest water depth	Zc (m)	mean	-14,52	-14,38	-14,39	-14,12	-14,45	-14,54
		s.d.	0,16	0,08	0,11	0,11	0,09	0,19
Migration rate	c (m/yr)	mean	25,94	37,2	31,99	20,57	23,69	31,63
		s.d.	18,59	11,69	12,75	34,68	33,65	22,7
Sediment flux	Q (t/m/yr)	mean	44,65	36,72	23,84	18,57	23,29	18,22
		s.d.	33,2	12,04	8,59	28,31	33,51	13,8

Smaller superimposed dunes are present with heights and wavelengths around 0.4-0.5 m and 10 m respectively, which have been retrieved from DEMs by pass-band filtering to focus on the primary bedforms. The primary dunes are slightly sinuous (sinuosity index values between 0.77 and 0.82), although D1 and D2 are clearly barkhan-type dunes with higher sinuosity indexes, indicative of stronger currents (e.g. Venditti et al., 2005). The dune asymmetry is important (asymmetry index between 0.22 and 0.58) with a permanent East polarity (Table 1).

A spatio-temporal variability of morphometric parameters was observed within and between dunes. The model showed a strong intra-dune variability, i.e. between sampled transects (Fig. 4-a). The mean wavelength varied significantly between dunes ($p < 0.05$) but not between surveys ($p > 0.05$). However, it did not vary significantly in the way between surveys on each dune ($p < 0.05$; Fig. 4-b). The smallest dunes (D4 to D6) seemed to show higher temporal variability in wavelength between surveys.

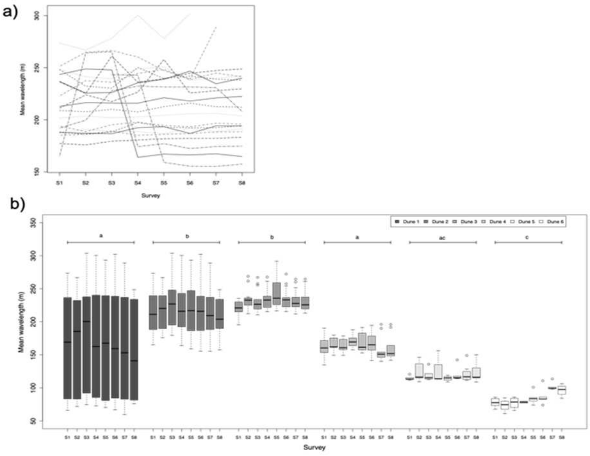

Figure 4. Spatio-temporal variability in dune wavelength highlighted by: a) an example of spatial variability measured along the 20-m spaced transects perpendicular to dune 2 (D2) during a survey, and b) the spatial and temporal variability between dunes and surveys together.

Over the study period, maximum height and maximum width varied significantly between dunes (Fig. 5-a,b respectively; Kruskal-Wallis tests: $\chi^2 = 42.60$, df = 5, $p = 4.46.10^{-8}$ and $\chi^2 = 35.82$, df = 5, $p = 1.03.10^{-6}$, respectively), as observed for height by Ernsten et al., 2006 over a semi-diurnal tidal cycle. Dunes are distributed according to a spatial West-East gradient, with the highest and largest dunes at the West (i.e. D1 to D3) and the smallest at the East (i.e. D4 to D6).

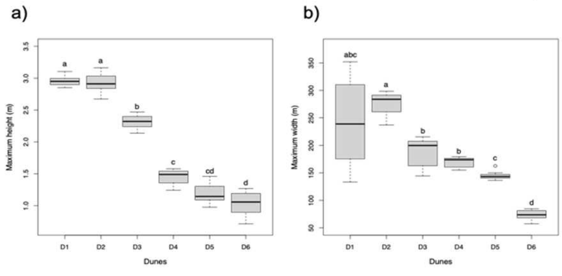

Figure 5. Comparison of maximum height (a) and maximum width (b) between dunes.

Only the dune D2 showed significantly a smaller maximum sinuosity index (Kruskal-Wallis tests: $\chi^2 = 13.47$, df = 5, p = 0.02).

4.3. Dune migration rates

At the scale of the whole studied time-period, the six dunes migrate toward the east with rates of the same order of magnitude, comprised between 20.57 m/yr (s.d. 34.68) and 37.20 m/yr (s.d. 11.69) (Table 1).These rates are similar to ones observed for dunes in the Dover Strait, some tens of kilometres away (Le Bot et al., 2000).

The six dunes display important migration rates towards the East during L1_L2, L4_L5 and L6_L7. During L2_L3 and L7_L8, migration decreases towards the East, even reverses towards the West (e.g. the smallest dunes D3, D4 and D5).

4.4. Dune associated sedimentary fluxes

- “Dune tracking” approach:

At the scale of the whole time-period, mean sediment fluxes are of the same order of magnitude for the 6 dunes, comprised between 18,22 ± 13,80 et 44,65 ± 33,20 t/m/yr and oriented towards the East (Table 1). The fluxes are higher for the largest dunes.

The 6 dunes display consistently the same time-evolution as the migration rates, in intensity and direction (see 4.3.2). This result was attended since the “Dune tracking” method is based on dune migration and morphology.

- Empirical approach:

First, the similar values obtained for sediment fluxes during L2_L3 (period with strong NE winds) with both methods (“Dune tracking”, empirical formulas) attest the consistency of the values, and, as fact, allow a validation of the values of sediment fluxes obtained for the 6 other time-periods (Table 2). Second, the data extracted from MARS3D and WWIII models show that, in these strong NE wind conditions, the flood period is dominant with a ratio between ebb and flood peaks varying between 0.5 for strong tides (end of L2-L3 period) and 0.8 for weak tides (beginning of L2-L3 period) (Fig 6-a). The free-surface elevation data, also shows that the flood peak is synchronized with the high tide while the ebb peak is synchronized with the low tide. The waves extracted from the WWIII model are consistent with the strong wind conditions coming from the North-East.

Table 2. Synthesis of the sediment fluxes (t/m/yr) estimated using the « Dune Tracking »method and an empirical approach over L2-L3 period. +/–: East/West direction of the sediment fluxes, respectively. D1 to D6 correspond to the 6 dunes.

	« Dune tracking » approach						*Empirical approach*		
	D1	*D2*	*D3*	*D4*	*D5*	*D6*	*Yalin adapted (1963)*	*Van Rijn (1984)*	*Wu et al. (2000)*
Sediment fluxes	*-15,91*	*41,49*	*22,38*	*-29,77*	*-16,50*	*-2,73*	*-25.98*	*-21.85*	*-9.86*

The results show that the fluxes strongly depend on the waves (e.g. maximum fluxes over the 27/03-30/03 period and the 14/04 where significant wave height is respectively 2.0 and 1.5m; Fig. 6-b,c), even if the flux maximums are not synchronized with the significant wave height maximums but moreover with the low tide.

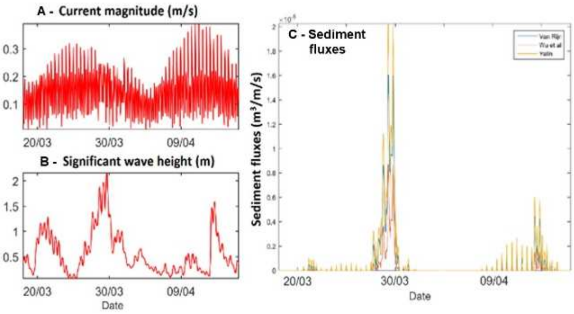

Figure 6. Realistic hydrodynamic conditions extracted from MARS3D and WW3 simulations over the L2-L3 period. Instantaneous sediment fluxes estimated using Yalin adapted (1963), Van Rijn (1984) and Wu et al. (2000) formulations.

In comparison, the current does not have a significant influence on these fluxes, except during the strong tides (and strong tidal current asymmetry) around the 11/04. Consequently, sediment flux is stronger during low tide and then more sediment is transported by currents on ebb period, bringing an explanation for the inversion of the migration direction.

4.5. Interrelations between dune morphodynamic parameters and forcings

The different parameters (dune morphology and migration rate, sediment fluxes, meteo-marine forcings) have been jointly analysed thanks to a STATIS analysis to inspect the correlations in-between in order to evaluate the spatio-temporal variability of dunes morphodynamics in relation with meteo-marine forcings.

The temporal analysis reveals a very strong interstructure since the 1st factorial plan gathers 93% of the variance with a strong correlation between 2D time tables defined by Rho Vectorial coefficients (a multivariate generalization for matrix of the squared Pearson correlation coefficient) [0.74-0.95], and is mainly carried by the D3 and D1 dunes. This F1 axis in compromise factorial plan accounts for the transverse morphology of the dunes (Fig. 7-a-1), with dunes of smaller dimensions and greater asymmetry for strong SW wind regimes and which present larger migration rates and associated sediment fluxes. The F2 axis indicates that the dunes are more sinuous for conditions of strong tidal currents and a regime of strong NE winds (Fig. 7-a-1).

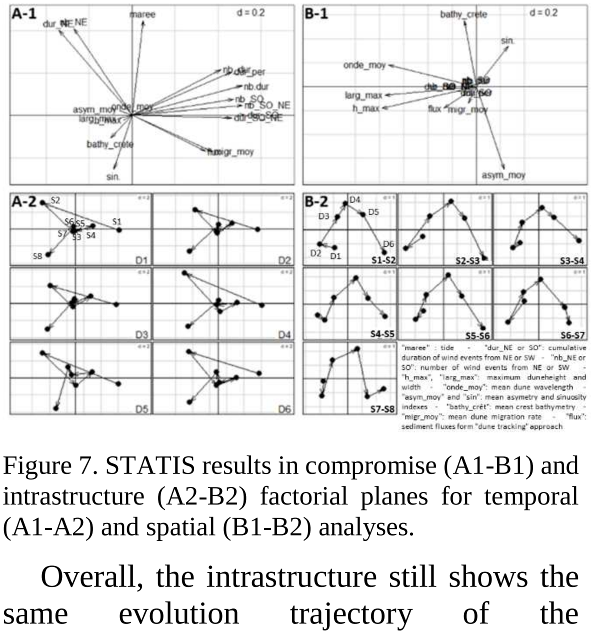

Figure 7. STATIS results in compromise (A1-B1) and intrastructure (A2-B2) factorial planes for temporal (A1-A2) and spatial (B1-B2) analyses.

Overall, the intrastructure still shows the same evolution trajectory of the characteristics of the dunes over time (Fig. 7-a-2). Distinct behaviors of all the dunes can be identified according to the periods, and confirm the 3 scenarios identified in 4.1.: the F1 axis distinguishes the period of strong and frequent SW winds (L1_L2; right part), the 2 periods of NE winds (L2_L3 and L7_L8; left part) and periods of more variable strong winds (L3_L4 to L6_L7; central position).

The spatial analysis reveals a strong, interstructure (but weaker than the temporal) with 85% of variance with lower correlations between 2D space tables defined by RV coefficients [0.56-0.92] carried by the 1st factorial axis, indicating that a large part of the variations in the morphodynamic characteristics of the dunes remains common. The rate of dune migration, sedimentary fluxes and meteo-marine forcings contribute very little to the inter-dune variability, which is mainly expressed at the level of morphology (Fig. 7-b-1). Overall, the infrastructure always shows the same trajectory whatever the period, with a passage from quadrant F1-/F2- to middle F1/F2+ then F1+/F2- from dune D1 to dune D6, supporting the existence of a West-East spatial morphological gradient (Fig. 7-b-2). We can distinguish 3 groups of dunes (D1 on one hand and D2, D4, D6 on the other hand) significantly different from a morphological point of view, while the dunes D3 and D5 present fluctuating similarities with one or another group.

5 CONCLUSION

In the framework of the wind turbine project off Dunkirk, a dune field has been monitored at a plurimonthly scale during 20 months to analyse dune morphology, migration and associated sediment fluxes in relation with meteo-marine forcings.

The main results indicate: (i) a West-East spatial morphological gradient within the dune field with, to the West, largest, more sinuous dunes with higher migration rates and sediment fluxes, suggesting an hydraulic attenuation along the dune field from West to East, in the direction of the main residual current, (ii) a similar dune response in terms of migration and sediment fluxes to meteo-marine scenarios, while the dune morphological parameters can evolve according to various trends, suggesting reorganization of sedimentary volumes within the dunes, (iii) a strong intra-dune and an weak interdune variability for some morphological parameters (e.g. height, width, wavelength), and (iv) reversal of some dunes when strong NE winds oppose the tidal residual and induce strong sediment fluxes toward the West, due to a main wave action at low tide during ebb phase, inversing the sediment transport in the West direction.

Some recommendations can be drawn up concerning the monitoring of dune fields in offshore wind farms. The spatio-temporal variability of dune morphodynamics at a plurimonthly time-scale suggests to conduct bathymetric surveys on the whole dune field and also on the whole individual dune shapes. The relations with meteo-marine forcings indicate that surveys are required : (i) at a pluri-monthly time-scale, and (ii) in particular, after the winter stormy period and after periods whith strong SO and NE winds.

6 ACKNOWLEDGEMENT

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7 REFERENCES

Bates D., Mächler M., Bolker B., Walker S. 2015. Fitting Linear Mixed-Effects Models Using lme4. J. Stat. Soft. 67(1), 1–48

Blanpain, O. 2009. Dynamique sédimentaire multiclasse : de l’étude des processus à la modélisation en Manche. Thèse de doctorat, Université de Rouen, 315 pp

Boudière, E., Maisondieu, C., Harduin, F., Accensi, M., Pineau-Guillou, L., Lepesqueur, J. 2013. A suitable metocea hindcast database for the design of marine energy converters. Int. J. Mar. Energy 3-4, e40-e52

Campmans, G.H.P., Roos, P.C., Vriend, H.J., Hulscher, S.J.M.H. 2018. The Influence of Storms on Sand Wave Evolution: A Nonlinear Idealized Modeling Approach. J. Geophys. Res. Earth Surf. 123, 2070–2086

Carter, L., Gavey, R., Talling, P.J., Liu, J.T., 2014. Insights into Submarine Geohazards from Breaks in Subsea Telecommunication Cables. Oceanography 27 (2), 58-67

Couldrey, A.J., Benson, T., Knaapen, M.A.F., Marten, K.V., Whitehouse, R.J.S., 2020. Morphological evolution of a barchan dune migrating past an offshore wind farm foundation. Earth Surf. Proc. Landf. 54(12), 2745-3068

Ernstsen, V.B., Noormets, R., Winter, C., Hebbeln, D., Bartholomä, A., Flemming, B.W., Bartholdy, J. 2006. Quantification of dune dynamics during a tidal cycle in an inlet channel of the Danish Wadden Sea. Geo-Mar. Lett. 26, 151-163

Fournier, M., Motelay-Massei, A., Massei, N., Aubert, M., Bakalowicz, M., Dupont, J.P. 2009. Investigation of Transport Processes inside Karst Aquifer by Means of STATIS. Groundwater 47, 391-400

Latapy, A., Héquette, A., Pouvreau, N., Weber, N.Robin-Chanteloup, J.B. 2019. Mesoscale morphological changes of nearshore sand banks since the early 19th century, and their influence on coastal dynamics, Northern France. J. Mar. Sci. Eng. 7, 73.

Le Bot, S., Trentesaux, A., Garlan, T., Berné, S., Chamley, H. 2000. Influence des tempêtes sur la mobilité des dunes tidales dans le détroit du Pas-de-Calais. Ocean. Acta, 23, 129–141

R Core Team 2022. R: A language and environment for statistical computing. Version 4.2.0. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

Robert, A.E., Quillien, N., Bacha, M., Caulle, C., Nexer, M., Parent, B., Garlan, T., Desroy, N. 2021. Sediment migrations drive the dynamic of macrobenthic ecosystems in subtidal sandy bedforms. Mar. Poll. Bull. 171, 11269.

Schmitt, T., Mitchell, N.C. 2014. Dune-associated sand fluxes at the nearshore termination of a banner sand bank (Helwick Sands, Bristol Channel). Cont. Shelf Res. 76, 64-74

Tonnon, P.K., Van Rijn, L.C., Walstra, D.J.R., 2007. The morphodynamic modelling of tidal sand waves on the shoreface. Coastal Engineering, 54, 279-296.

van Rijn L.C., 1984. Sediment transport, part I: bed load transport. J. Hydraul. Eng., 110(10), 1431-1456.

Venditti, J., Church, M., Bennett, S., 2005. On the transition between 2D and 3D dunes. Sedimentology. 52. 1343 – 1359

Wu, W., Wang, S. S. Y., Jia, Y., 2000. Non uniform sediment transport in alluvial rivers. J. Hydr. Res., 38, 427 - 434.

Yalin, M. S., 1963. An expression for bedload transportation. J. Hydr. Division Am. Soc. Civ. Engi., 90, 105 - 119.

What is a dune?
Towards a homogenisation of the nomenclature of bedforms

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ABSTRACT: Despite a workshop and recommendations published 30 years ago on the nomenclature and description of large flow-transverse bedforms, many terms are still in use. It is uncertain whether these names are used because of intrinsic differences between bedform types (e.g. river dunes, marine sand waves, sediment waves) or for other reasons. We would like to have an open discussion about this topic. We are conducting a literature survey to provide a comprehensive basis of the current terms used. We will invite MARID participants to share their thoughts and ideas about the subject and conduct an online survey to reach the wider community. To facilitate the discussion, we propose a preliminary classification.

1 INTRODUCTION

In 1990, Gail M. Ashley published a manuscript entitled “Classification of large-scale subaqueous bedforms: a new look at an old problem”. She reported on a symposium conducted in Texas three years earlier, during which the nomenclature of large-scale subaqueous flow-transverse bedforms was discussed by 27 researchers. The symposium panel (consisting of 19 participants) proposed to name all large-scale subaqueous bedforms “dunes” instead of the variety of terms used until then (e.g. megaripples, dunes, sand waves, etc.). They also provided a set of primary and secondary descriptors to describe dune properties (Table 1).

Despite the recommendations given in Ashley (1990), a plethora of terms continues to be used to describe large-scale flow-transverse bedforms, often without clear definition or distinction between the different nomenclature. For example, (marine) dunes and sand waves are used interchangeably in many contexts. Smaller bedforms superimposed on larger ones may be referred to as megaripples or secondary dunes. It is currently unclear if different terms are used due to intrinsic differences between bedform types, or if it is due to the different scientific communities. Ashley (1990) already noted that the “poor communication among scientists and engineers has perpetuated the multiplicity of terms”. Researchers from fluvial, coastal or deep marine environments, from industry or academia, from various disciplines, such as sedimentology, oceanography, coastal and offshore engineering or geomorphology may use a specific vocabulary. Furthermore, terminology may be different depending on the country or working group in which they work.

We therefore feel the need to bring together researchers working on as many environments and disciplines as possible to discuss and define the different types of flow-transverse bedforms. Everyone is invited to participate in the discussion and bring their own expertise and views. On this basis, we aim to produce an updated and extended classification scheme.

Table 1: Classification scheme recommended by the SEPM Bedforms and Bedding Structures Research Symposium (Ashley, 1990)

Subaqueous Dunes

First Order Descriptions (necessary)

Size: Spacing =	small 0.6-5 m	medium 5-10 m	large 10-100 m	very large > 100m
Height* =	0.075-0.4 m	0.4-0.75 m	0.75-5m	> 5 m

Shape: 2-Dimensionnal
3-Dimensionnal

Second Order Descriptors (important)

- Superposition: simple or compound (sizes and relative orientation)
- Sediment characteristics (size, sorting)

Third Order Descriptors (useful)

- Bedform profile (stoss and lee slope lengths and angles)
- Fullbeddedness (fraction of bed covered by bedforms)
- Flow structure (time-velocity characteristics)
- Relative strength of opposite flows
- Dune behaviour-migration history (vertical and horizontal accretion)

*Height calculated using the equation $H = 0.0677 L^{0.8098}$ (Flemming, 1988)

2 METHODS

2.1 Literature survey

A survey of the scientific literature related to large-scale flow transverse bedform is done to identify some common definitions and specific names, possibly depending on the communities. Some of the characteristics which are identified for each paper include: bedform type (e.g. number of times the terms “dune”, “sand wave”, “megaripple”, “sediment wave”, “bedform”, etc. are used), author affiliation, environment in which the bedforms are found (e.g. flume, river, tidal inlet, continental shelf, continental slope, deep environment, etc.), the processes forming the bedforms (e.g. river flow, tidal currents, bottom currents, internal waves, etc.), bedform characteristics (height, length, migration rate, presence of secondary bedform, etc.) and other relevant information (e.g. water depth, sediment type, etc.).

The database will be analysed to assess if there is a nomenclature dominantly used depending on e.g., environment or affiliation. It can serve as a basis for the discussion by providing a comprehensive and detailed depiction of the many names still used for flow-transverse bedforms, and by whom they are used.

The database will be made publicly available for researchers to use and further develop it.

2.2 Discussion during MARID

During the conference, we would like to invite interested scientists to share with us their ideas and thoughts.

2.3 Community survey

A survey will be carried out after MARID VII in order to get some quantitative and qualitative information. This survey will be widely distributed in order to provide the opportunity for as many scientists as possible (also those who were not at MARID) to share their views on the subject.

3 DISCUSSION POINTS

In this section, we address the three topics which were raised by Ashley (1990). We provide an update about these topics in view of the recent literature and suggest discussion points. Preliminary results of the literature survey are given and a classification scheme is suggested in order to foster a lively conversation between the participants.

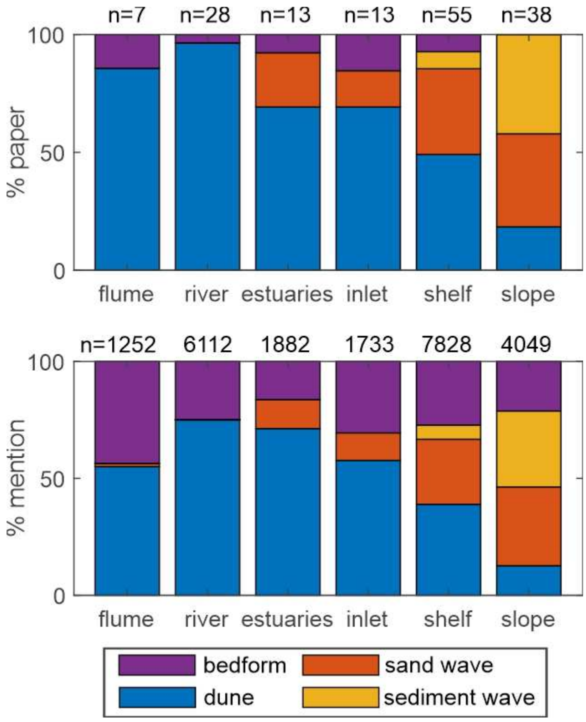

Figure 1. Preliminary results of the literature survey. Upper panel: percentage of papers depending on main bedform type and environment; lower panel: percentage of mention of bedform type for all the papers in each environment. n refers to the total number of papers or mention for the specific environment

3.1 Types of flow transverse bedforms

Ashley (1990) stated that “1) all large flow-transverse bedforms are a similar phenomena; the morphologic variety reflects the response to channelization, fluctuating water level, speed, and direction; 2) large bedforms occur as a continuum of sizes, not as discrete groups; and (3) large bedforms should be given one name rather than be split into classes.”

The workshop participants managed to agree on the term “dune” and Ashley (1990) recommended using this term for future communication. However, until now, there is still a variety of terms used to describe large flow transverse bedforms, as our literature survey illustrates (Figure 1). In laboratory and fluvial environments, only the terms “dune” and “bedform” are used. However, in marine environments, “sand wave” and “sediment wave” are also used, more and more as the environment gets deeper.

The literature survey highlights some developments which happened since the publication of Ashley (1990). The use of multibeam echosounder surveys has made high-resolution mapping possible for large portions of the seabed. Bedforms have now been identified in many regions of the world which previously could not be mapped accurately, including on the continental shelf, slope and abyssal plain. These bedforms have been named dunes, cyclic steps, sediment waves, or more precisely mud waves, sand waves or gravel waves, if the sediment in which they form is known.

The main question which we need to answer as a community: is there a physical difference between bedform types from varied environments?

Ashley (1990) recognised three environments with different settings: rivers, sandy coastal embayments and continental shelves. For the literature review, we divided the environments into 6 categories: (1) flume with unidirectional flows, very low water depth (typically less than 50 cm) and relatively high Froude numbers (typically 0.3-0.6); (2) rivers with channelized unidirectional flow, and a wide range of grain sizes and hydrologic characteristics; (3) estuaries with channelized flow, tidally-varying currents (either with a full flow reversal, but sometimes with flow variations without reversal), seasonal river flow variations and possible influence of estuarine circulation; (4) tidal inlets, with channelized flow and tidally reversing currents; (5) continental shelf, with relatively deep, unchannelized flow, with the influence of tidal currents, wind and wave-generated currents and bottom currents; and (6) slope with the influence of internal tides and waves, along-slope bottom currents and turbidity flows.

Considering the wide variety of sediment types, water depths and hydrodynamics in these environments, we are questioning if there is an intrinsic difference between river, tidal and marine shallow and deep-water bedforms. Is there a continuum of bedforms or can separate entities be defined since the driving hydrodynamic forcings creating them, their morphology, interaction with the flow and internal structure are different?

In order to determine the different bedform types and their properties, we suggest some points to discuss:

(1) **Origin.** Bedforms generally develop as the flow transports and deposits sediment. Research about the origin and growth of bedforms has been carried out in laboratory settings with unidirectional flow and waves, and with numerical simulations on unidirectional and reversing flows (tidal currents and waves). Against this background, the question can be asked: does bedform formation vary depending on the hydrodynamics (unidirectional currents, tidal currents, wind waves, internal waves, etc.) and sedimentological properties (e.g. muddy, sandy and gravelly sediment)?

(2) **Interaction with the water surface and link between water depth and bedform size.** In river environments, dunes are often opposed to ripples. River dunes are defined as bedforms which interact with the water surface and whose size is controlled by water depth (Bradley and Venditti, 2017). Ripples are small elements that do not interact with the water surface and with sizes controlled by sediment grain size and water depth (Venditti, 2013). Bedforms found on the continental shelf can be very large (up to > 30 m in height, (Franzetti et al., 2013)) but are often relatively small compared to the water depth and are therefore unlikely to interact with the water surface. Their height may also not be controlled by water depth but, at least some cases, depth controls their steepness (Damen et al., 2018). Therefore, we can wonder if river and marine bedforms are different bedform types based on their interaction with the water surface and depth.

(3) **Bedform morphology and influence on hydrodynamics.** Hulscher and Dohmen-Janssen (2005) made a distinction between river dunes and marine sand waves. They first noted their similarities, especially their large spatial scales compared to the water depth, which differentiate them from ripples and megaripples. They then highlighted their difference: marine sand waves were defined as sinusoidal-like bed features, quite symmetric with small temporal variations (migration speed and amplitude) compared to river dunes; and river dunes are described as asymmetric, often with flow separation, migrating fast, and being more pronounced during river floods than during low river discharge. Since then, however, it has been demonstrated that bedforms in large rivers have low to intermediate lee side angles (Cisneros et al., 2020). They are therefore not as steep as angle-of-repose bedforms which typically form in shallow water (e.g. flumes) and are unlikely to produce a permanent flow separation. Therefore, we can ask: is flow above marine bedforms significantly different from flow above river dunes? Obviously, flow in tidal environments reverses, so there will be noticeable differences. But, if we think about the time during which flow is going in one direction, is there some differences due to bedform morphology? Venditti (2013) noted that ripples are generally steeper than dunes, but with an overlap suggesting that larger aspect ratios (height / length) are not a mutually exclusive property of either ripples or dunes. Until now, there has not been a systematic study of the steepness of marine bedforms which would help in assessing the variability of their slopes and clarify if there is a notable difference between river and marine bedform slope/steepness.

(4) **Internal structure**. Bedform stratification and their deposits are important for interpreting past flow conditions and environments. Differences can be recognised between small-scale cross-laminations created by ripples and large-scale cross-bedded sequences created by dunes, but also between bedforms formed in rivers and tidal environments, as well as depending on

bedform morphology, notably three-dimensionality and bedform superposition (Dalrymple and Rhodes, 1995). Wynn and Masson (2008) described sediment waves as very large depositional features (length of several km, height up to 50 m) formed by bottom currents with poorly developed laminae and intense bioturbation resulting from steady quasi-continuous sedimentation. Cartigny et al. (2011) proposed a classification of sediment waves into dunes, antidunes and cyclic steps based on their morphology, stratigraphy and migration. Dunes develop at Froude number < 1, migrate downslope, and have an internal structure showing some lee-side cross-bedding. Anti-dunes form at Froude number between 1 and 2, can be migrating down or upslope, and their internal structure is not well known. Cyclic steps, created by turbidity currents, form at very high Froude numbers (>2), are migrating upslope, and their internal structure shows parallel or cross bedding from their stoss sides. Based on this description of bedforms, it seems that their internal structure could help in differentiating some bedform types.

(5) **Continuum in environments.** Until now, we treated the different environments, and especially river and marine, as separate and distinct environments. However, there are transition zones between rivers and oceans, namely estuaries, in which numerous bedforms are found. The hydrodynamics, sedimentological inventory and water depth characteristics are intermediary between fluvial and marine settings. Furthermore, the marine environment also presents a variety of hydrodynamic forcings and sedimentary properties. Therefore, there is not just one type of "marine bedforms" but a variety of them, such as for example, the large fields of bedforms controlled by tidal influence on the Dutch continental shelf (Damen et al., 2018), coarse-grained bedforms in the tidally-dominated Irish Sea (Van Landeghem et al., 2009), deep-water bedforms formed by bottom currents on drowned isolated carbonate terraces (Miramontes et al., 2019) or very large bedforms on the upper continental slope generated by episodic internal waves (Reeder et al., 2011).

We repeat here the first questions asked by Ashley (1990) "do all large-scale bedforms relate to the same hydrodynamic phenomenon, and do they occur in a continuum of sizes or as discrete groups? If they are all related, is there a single acceptable term?" We propose a tentative classification (Figure 2) which we are happy to discuss. This classification defines "dunes" following Ashley (1990) as all the large-flow transverse bedforms found in fluvial, estuarine and marine environments, with the precision that they show cross-bedded stratigraphy. This distinguishes them from ripples, which are small in size, from sediment waves, which are much larger, form in muddy sediment and show laminar stratigraphy, and anti-dunes or cyclic steps, which form at very high Froude numbers. We also recognise a number of different types of dunes (Figure 2, not all are represented here).

3.2 Bedform superimposition

Ashley (1990) asked "what is the significance of bedform superposition?". First, we note that since 1990, the word 'superimposed' has been used more frequently than 'superposed'. The definitions given by Oxford Languages are as follow: (1) Superposed: placed on or above something else, especially so that both things coincide; (2) Superimposed: placed or laid over something else, typically so that both things are still evident. Since both definitions are roughly equivalent and superimposed is the term predominantly used in recent publications, we will keep on using it here.

The question that was discussed in 1987 and can still be discussed is: are superimposed bedforms inherently different from large primary bedforms in terms of flow and sediment transport? The panel concluded that superimposition "appears to be a function of available space and time for growth and migration and reflects complexity of conditions rather than fundamental

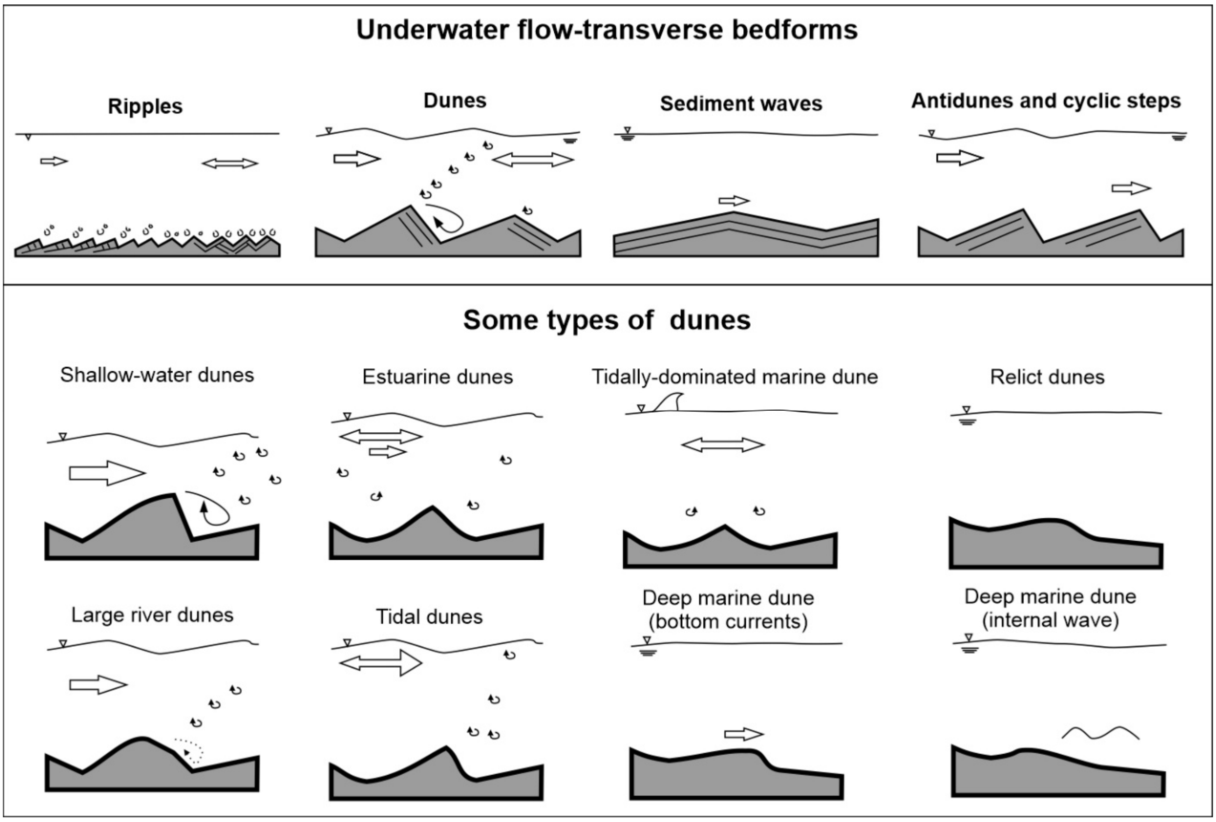

Figure 2. Top: at least 4 types of flow-transverse bedforms are recognised and differentiated based on their origin, interaction with the flow, their morphology and their stratigraphy. Bottom: examples of dune types

processes of bedform genesis”. They suggested that bedform superimposition should be kept as second-order descriptor (simple or compound bedforms) rather than a classification term.

However, superimposed bedforms are still called by a variety of terms, such as “sand waves” (Venditti et al., 2005), “superimposed dunes” (Ernstsen et al., 2006), megaripples (Bellec et al., 2019) or simply “secondary bedforms” (Zomer et al., 2021). Using superimposition or bedform size as a classifying parameter implies that there is a fundamental difference between large simple bedforms and superimposed or compound forms.

3.3 Descriptors

The third discussion point of Ashley (1990) concerned the descriptors of bedform morphology and behaviour. These descriptors were chosen to be hydraulically significant in order to provide a link between internal structure, morphology and the flow that created the bedforms. They should improve communication amongst scientists working on bedforms or their deposits.

Following the progress of bedform research during the last 30 years, we believe that the descriptors given by Ashley (1990) (Table 1) can be updated to better consider the relevant bedform parameters. For example, the definition of “bedform profile” can be made more precise by including some information such as the mean and maximum lee side angles, as well as the position of the maximum angle. The anthropogenic activities (e.g. dredging) should also be detailed, as they may have a strong impact on dune characteristics.

Table 2: Some descriptive parameters of underwater dunes

Morphology	
Size[1]	Small: L=0.6-5 m Medium: L= 5-10 m Large: L= 10-100 m Very large L= > 100m
3D organisation[2] and fullbeddedness[1]	Isolated, field, on a bank; fraction of bed covered by bedforms
Three-dimensionality	Non-dimensional span, bifurcation index, morphological type[2] (barchans, rhomboidal, trochoidal, transverse)
2D shape[3,4]	Asymmetry, stoss and lee slope lengths and mean angles, value and position of maximum angle
Hierarchy	Simple or compound, primary or secondary
Environment	
Water depth	Total water depth and relative bedform height
Anthropogenic impact	Dredging activities, offshore construction
Sedimentology	
Sediment characteristics	Size, sorting, skewness
Stratigraphy	Internal structure
Hydrodynamics	
Main hydrodynamics	River discharge, tidal flow, waves, internal waves
Flow structure	Velocity and turbulence characteristics
Flow variation	In time and/or space
If tidal flow	Relative strength of opposite flows
Biological activity	
Biota and fish	Distribution
Dynamics	
Dune behaviour	Migration history and rates

[1] Ashley (1990)
[2] Garlan et al. (2016)
[3] Cisneros et al (2021)
[4] Lefebvre et al. (2021)

We also question the structure of the descriptive parameters (first, second and third order parameters). It seems to us that the descriptors, and especially their ranking, was done from a sedimentological point of view, with the descriptor orders reflecting the important parameters which are going to influence bedform deposit. Considering the range of scientists studying bedforms and the variety of applications, the focus on bedform deposit can be questioned. Therefore, we think there might not be a need for classification between different order descriptors, but with other parameters such as morphology, environment, sedimentology, hydrodynamics, biological activity and dynamics (Table 2).

4 CONCLUSIONS

Despite the recommendation on the nomenclature of large flow-transverse bedforms given over 30 years ago, a variety of terms are currently in use. We propose to discuss and clarify the classification of large flow-transverse bedforms.

5 ACKNOWLEDGEMENT

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6 REFERENCES

Ashley, G. M.: Classification of large-scale subaqueous bedforms: A new look at an old problem, J. Sediment. Res., 60, 160-172, https://doi.org/10.2110/JSR.60.160, 1990.

Bellec, V. K., Bøe, R., Bjarnadóttir, L. R., Albretsen, J., Dolan, M., Chand, S., Thorsnes, T., Jakobsen, F. W., Nixon, C., Plassen, L., Jensen, H., Baeten, N., Olsen, H., and Elvenes, S.: Sandbanks, sandwaves and megaripples on Spitsbergenbanken, Barents Sea, Mar. Geol., 416, 105998, https://doi.org/10.1016/j.margeo.2019.105998, 2019.

Bradley, R. W. and Venditti, J. G.: Reevaluating dune scaling relations, Earth-Science Reviews, 165, 356-376, https://doi.org/10.1016/j.earscirev.2016.11.004, 2017.

Cartigny, M. J. B., Postma, G., van den Berg, J. H., and Mastbergen, D. R.: A comparative study of sediment waves and cyclic steps based on geometries, internal structures and numerical modeling, Mar. Geol., 280, 40-56, https://doi.org/10.1016/j.margeo.2010.11.006, 2011.

Cisneros, J., Best, J., van Dijk, T., de Almeida, R. P., Amsler, M., Boldt, J., Freitas, B., Galeazzi, C., Huizinga, R., Ianniruberto, M., Ma, H. B., Nittrouer, J. A., Oberg, K., Orfeo, O., Parsons, D., Szupiany, R., Wang, P., and Zhang, Y. F.: Dunes in the world's big rivers are characterized by low-angle lee-side slopes and a complex shape, Nat. Geosci., 13, 156-+, https://doi.org/10.1038/s41561-019-0511-7, 2020.

Dalrymple, R. W. and Rhodes, R. N.: Chapter 13 Estuarine Dunes and Bars, in: Dev. Sedimentol., edited by: Perillo, G. M. E., Elsevier, 359-422, 1995.

Damen, J. M., van Dijk, T. A. G. P., and Hulscher, S. J. M. H.: Spatially Varying Environmental Properties Controlling Observed Sand Wave Morphology, Journal of Geophysical Research: Earth Surface, 123, https://doi.org/10.1002/2017JF004322, 2018.

Ernstsen, V. B., Noormets, R., Winter, C., Hebbeln, D., Bartholomä, A., Flemming, B. W., and Bartholdy, J.: Quantification of dune dynamics during a tidal cycle in an inlet channel of the Danish Wadden Sea, Geo-Mar. Lett., 26, 151-163, https://doi.org/10.1007/s00367-006-0026-2, 2006.

Franzetti, M., Le Roy, P., Delacourt, C., Garlan, T., Cancouët, R., Sukhovich, A., and Deschamps, A.: Giant dune morphologies and dynamics in a deep continental shelf environment: Example of the banc du four (Western Brittany, France), Mar. Geol., 346, 17-30, https://doi.org/10.1016/j.margeo.2013.07.014, 2013.

Garlan, T., Brenon, E., Marchès, E., and Blanpain, O.: From regional variability of the morphology of dunes to a new method of their classification, MARID 2016. Fifth International Conference on Marine and River Dune Dynamics, Caernarfon, United Kingdom, 4– 6 April 2016,

Hulscher, S. J. M. H. and Dohmen-Janssen, C. M.: Introduction to special section on Marine Sand Wave and River Dune Dynamics, Journal of Geophysical Research: Earth Surface, 110, https://doi.org/10.1029/2005JF000404, 2005.

Lefebvre, A., Herrling, G., Becker, M., Zorndt, A., Krämer, K., and Winter, C.: Morphology of estuarine bedforms, Weser Estuary, Germany, Earth Surf. Processes Landforms, https://doi.org/10.1002/esp.5243, 2021.

Miramontes, E., Jorry, S. J., Jouet, G., Counts, J. W., Courgeon, S., Le Roy, P., Guerin, C., and Hernández-Molina, F. J.: Deep-water dunes on drowned isolated carbonate terraces (Mozambique Channel, south-west Indian Ocean), Sedimentology, 66, 1222-1242, https://doi.org/https://doi.org/10.1111/sed.12572, 2019.

Reeder, D. B., Ma, B. B., and Yang, Y. J.: Very large subaqueous sand dunes on the upper continental slope in the South China Sea generated by episodic, shoaling deep-water internal solitary waves, Mar. Geol., 279, 12-18, https://doi.org/10.1016/j.margeo.2010.10.009, 2011.

Van Landeghem, K. J. J., Wheeler, A. J., Mitchell, N. C., and Sutton, G.: Variations in sediment wave dimensions across the tidally dominated Irish Sea, NW Europe, Mar. Geol., 263, 108-119, https://doi.org/10.1016/j.margeo.2009.04.003, 2009.

Venditti, J. G.: Bedforms in sand-bedded rivers, in: Treatise on Geomorphology, edited by: Shroder, J., and Wohl, E., Academic Press, San Diego, CA, 137-162, 10.1016/B978-0-12-374739-6.00235-9, 2013.

Venditti, J. G., Church, M., and Bennett, S. J.: Morphodynamics of small-scale superimposed sand waves over migrating dune bed forms, Water Resour. Res., 41, https://doi.org/10.1029/2004WR003461, 2005.

Wynn, R. B. and Masson, D. G.: Chapter 15 Sediment Waves and Bedforms, in: Dev. Sedimentol., edited by: Rebesco, M., and Camerlenghi, A., Elsevier, 289-300, 10.1016/S0070-4571(08)10015-2, 2008.

Zomer, J. Y., Naqshband, S., Vermeulen, B., and Hoitink, A. J. F.: Rapidly Migrating Secondary Bedforms Can Persist on the Lee of Slowly Migrating Primary River Dunes, Journal of Geophysical Research: Earth Surface, 126, e2020JF005918, https://doi.org/doi.org/10.1029 /2020JF005918, 2021.