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Introduction to special section on Marine Sand Wave and River Dune Dynamics

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[1] Marine sand waves and river dunes are rhythmic patterns, formed at the interface between a sandy bed and turbulent flows, driven by tidal and river currents. Their origin, development, and dynamics are far from being fully understood. To enhance the discussion on this topic we organized the international conference Marine Sand Wave and River Dune Dynamics (MARID) in April 2004 in Enschede, Netherlands. Scientific papers that originated from the MARID conference are presented in this special section. This introduction places these papers in the context of recent progress.

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1. Introduction

[2] Rhythmic patterns are common features in nature. Prominent examples are the patterns formed on the interface of a mobile sandy bed and turbulent flow, due to currents, tides, wind waves or other forcing mechanisms. These bed patterns or bed forms vary in both spatial and temporal scales, from small-scale bed ripples (spacing on the order of centimeters) to large-scale tidal sand banks (spacing on the order of 5 km). In this paper and in this special issue, we focus on a cluster of large-scale features, i.e., marine sand waves and river dunes, occurring in rivers, estuaries and seas all over the world.

[3] Sand waves and river dunes are interesting both from a practical and from a scientific point of view. Sand waves, and more particularly their migrating troughs, are important features for pipelines buried under the seabed, because they should be prevented from being uncovered [*Németh et al.*, 2003]. This also holds for tunnels below rivers: dunes can become a threat here (e.g., the temporal exposure of a tunnel under the Rio Paraná, Argentina, due to large migrating dunes [*Amsler and García*, 1997; *Amsler and Schreider*, 1999]). The height of the crests of sand waves and river dunes determine the local water depth. Although it seems that in the Dutch section of the river Rhine dunes do not hinder navigation significantly [*Haitel and Dohmen-Janssen*, 2005], this situation may be different in other rivers. At least in the North Sea and the Bisanseto Sea in Japan, it is known that the crests of sand waves can harm navigation, leading to a need for accurate monitoring and possibly intervention by dredging [*Knaapen and Hulscher*, 2002]. A more indirect engineering impact of sand waves and river dunes stems from the fact that they are an important source of hydraulic roughness. Understanding their effect on hydraulic roughness is crucial for accurate predictions of extreme water levels during river floods or storm setup along the coasts.

[4] The origin and dynamics of these bed forms are ill understood. For instance, we are still unable to describe or to quantify the feedback between turbulent flow and bed form evolution, nor do we know what causes sand waves to vary in terms of wavelength or amplitude, even within one patch of sand waves. The underlying causes of variations within a patch or between patches can be physical processes, or they might have a stochastic nature. The challenge of fully understanding and predicting the dynamics of sand waves and river dunes motivated the MARID conference (Marine Sand Wave and River Dune Dynamics), which was held in Enschede, Netherlands in April 2004, as a follow-up of the SandWave Dynamics Workshop held in Lille, France, in 2000. At the conference the state-of-the art research on river dunes and marine sand waves was discussed, both from a scientific and from a practical point of view. This special section presents scientific papers that originated from the MARID conference. In this introduction we aim to place these papers in the context of recent progress.

[5] The outline of this paper is as follows: Section 2 provides an overview of similarities and differences between river dunes and marine sand waves. The papers on river dunes are introduced in section 3, followed by an introduction to the marine sand wave papers in section 4. In section 5 we discuss processes leading to river dune and sand wave formation and we link them to related rhythmic features. Section 6 concludes with several challenges we foresee for future research.

2. Similarities and Differences Between River Dunes and Marine Sand Waves

[6] River sand dunes and marine sand waves are bed features that are commonly found in sandy rivers and sandy coastal seas all over the world. They are similar enough to motivate a discussion of them together. They also differ in a number of aspects. A short overview is presented here.

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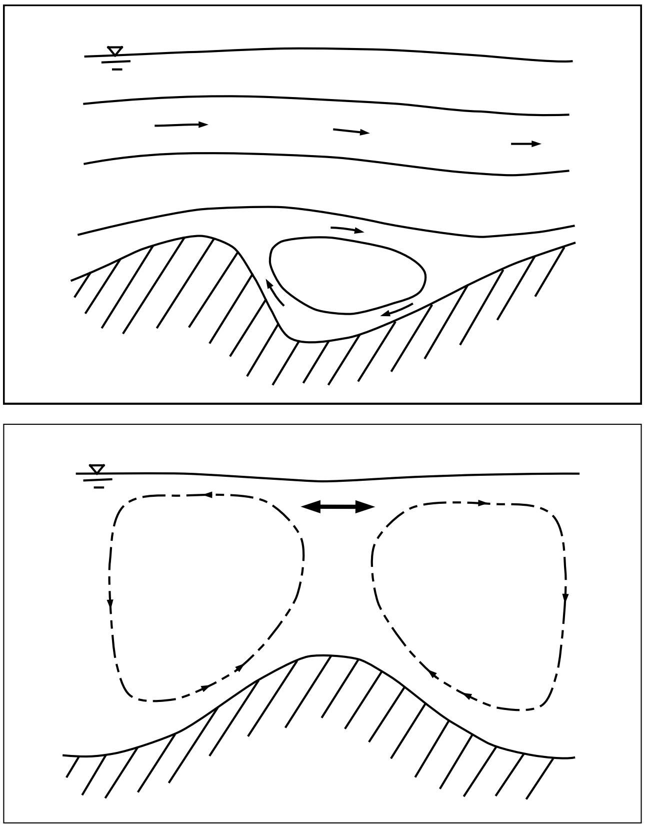

Figure 1. (top) Schematic presentation of the flow over river dunes. Note the flow separation which is typical for asymmetric river dunes. (bottom) Schematic presentation of the tidal flow above sand waves. The dashed vortices above the sand waves indicate tidal-averaged circulations being much weaker than the instantaneous tidal flow.

[7] Both river dunes and marine sand waves have wavelengths significantly larger than the water depth, and therefore differ from smaller-scale features such as megaripples or ripples. They both are referred to as 2-D features, i.e., in general their crests are much longer than their spacings. Sand waves and river dunes are both oriented perpendicular to the main (tidal) current, which is believed to be responsible for providing the energy to make the features emerge. Interaction (shear) between the near-bed flow and the sandy bed makes the bed unstable, so that the rhythmic features start to grow. The natural tendency for sand grains to move downhill provides a counteracting mechanism in both cases. We observe that sand wave amplitudes are at most 10% of the flow depth, whereas laboratory experiments show that river dunes can grow much larger. However, this is rarely observed in the field, presumably because the duration of floods limits the period in which dunes grow. A further similarity is that both sand waves and river dunes may coexist with both smaller-scale features (megaripples, ripples) and large-scale features (sand banks, alternate bars). In both sand waves and river dunes, near-bed vertical flow vortices tend to form with the bed features, illustrating the role of turbulence. However, these effects manifest themselves quite differently in rivers and tidal seas due to the unidirectional/nonunidirectional nature of the forcing flow (Figure 1).

[8] River dunes tend to grow, both in wavelength as well as in height, during flood events in rivers. The dunes are typically asymmetric and above a certain amplitude and shape the flow may separate from the crest, i.e., generating a flow recirculation zone behind the crest. This so-called flow separation is often observed in laboratory dunes. However, it is not always observed in the field, mainly for two reasons: (1) the lee side angles of river dunes are less than those in the laboratory, and (2) detailed measurements in the field are harder to get. River dunes migrate quite fast, in the order of one wavelength per day. After a flood, the amplitudes tend to decrease again, meaning that river dunes are only prominent part of the time.

[9] Marine sand waves are sinusoidal-like bed features, commonly occurring in sandy shallow, coastal seas in which tidal motion generates strong enough shear stresses at the bed to induce sediment transport. Sand waves can be very symmetric. The driving generation force is the M2-tidal motion. Other tidal components, as well as residual motion, lead to migration and shape asymmetry. During the stormy season, sand waves might decrease in amplitude. We observe that temporal variations of marine sand waves, both in migration speed and in amplitude, are much smaller than those of river dunes.

[10] In short, both sand waves and dunes are related to turbulent flows and they are, each in their own way, connected with flow vortices in the vertical plane. Sand waves are less pronounced and less dynamic than dunes; dunes only become pronounced during river floods and can be absent otherwise.

3. River Dunes

[11] Because of the significant dimensions of dunes when compared to water depth the flow field is significantly influenced by the presence of dunes. This interaction increases when dunes become so steep that the flow separates behind the crest and a large flow separation zone is formed behind the dune. Details of the mean and turbulent flow field determine the shear stress and corresponding sediment transport rates over the dune, and hence the resulting dune evolution. We must therefore understand the fluid dynamics of river dunes. A review and some future research directions on this topic are presented in the paper by *Best* [2005].

[12] Knowledge on morphodynamics of river dunes is collected through measurements, both in the field and in laboratory flumes, as well as through development of numerical models. Field observations have shown that river dunes can vary in shape, both in the direction of the overlying flow, e.g., low or steep angle lee sides, or perpendicular to the flow, e.g., two-dimensional features with relatively straight crest lines, or highly three-dimensional features. Dunes with low-angle lee sides are, for example, found in the Fraser Estuary, Canada [*Kostaschuk and Best*, 2005], whereas highly three-dimensional dunes are observed in the wide mouth of the Rio Paraná, Argentina [*Parsons et al.*, 2005].

[13] River dunes develop during floods as a result of the increasing discharge, flow velocity and bed shear stress. Dunes form or degrade due to the integrated erosion and sedimentation processes, which require time. Dune devel-

opment is therefore delayed relative to changing discharges, leading to a hysteresis in dune properties when plotted against discharge [e.g., *Ten Brinke et al.*, 1999]. *Kostaschuk and Best* [2005] show that dunes in the Fraser Estuary, Canada, also show a response to variations in (unidirectional) discharge on a much shorter timescale, i.e., that of the tidal period.

[14] In flume experiments, one is able to focus on details of river dune dynamics. For example, the composition and availability of the sediment is an important parameter that determines dune development. Their effects on initial dune development and on dune trough scour are described by *Carling et al.* [2005] and by *Kleinhans* [2005], respectively.

[15] In addition to straight-crested 2-D and more irregular 3-D bed forms, barchan dunes can exist. These are formed in case of a limited availability of sediment and are especially common in aeolian situations, i.e., deserts [*Bagnold*, 1941]. Despite the differences, knowledge on aeolian dunes may increase understanding of subaqeous dunes and vice versa. A nice example of such a study is the work by *Hersen* [2005], who simulated large barchan dunes, commonly observed in deserts, in a small-scale subaqeous laboratory experiment. The formation of barchan dunes also depends on sediment composition, as explained by *Ernstsen et al.* [2005].

[16] In addition to dunes, smaller-scale bed forms exist, in some cases superimposed on the larger dunes. Understanding the generation of small-scale bed forms and the mechanisms that limit their growth may also increase insight in the evolution of dunes. The study of *Langlois and Valence* [2005] on sand ripples under steady laminar shear flow aims to increase this understanding.

[17] The papers on river dunes from the MARID special section mainly cover experimental research on this topic. However, research also focuses on modeling river dune development. The first models to predict dune properties consisted of relatively simple formulations to predict equilibrium dune dimensions as a function of flow characteristics [e.g., *Yalin*, 1964; *Allen*, 1978; *Van Rijn*, 1984]. *Allen* [1978] included the delayed response to changing discharges in the form of a relaxation equation. The generation of dunes has often been modeled using linear stability analyses [e.g., *Kennedy*, 1963; *Engelund*, 1970; *Fredsøe*, 1974] or weakly nonlinear stability analyses [e.g., *Pekeris and Shkoller*, 1967; *Watanabe et al.*, 2001; *Yamaguchi and Izumi*, 2002]. While linear stability analysis predicts wavelength and evolution timescale, it does not describe amplitude evolution itself.

[18] An important aspect in river dune development is the occurrence of flow separation and reattachment behind the relatively steep asymmetric dunes. This may restrict the applicability of stability analyses. Recently, advanced turbulence models [e.g., *Yoon and Patel*, 1996; *Stansby and Zhou*, 1998] or even direct numerical simulation and large eddy simulation models are being developed to describe the flow in this separation zone. At present, however, the calculation intensity of these models prevents their inclusion in models describing dune development. A new type of model to simulate the development of bed forms has been presented by *Niño et al.* [2002] and is based on probabilities of deposition and entrainment over disturbances on the bed. An alternative approach has been followed by *Paarlberg et al.* [2005]. They adopted the approach of *Kroy et al.* [2002], who developed a model for aeolian dunes in which they included flow separation in a parameterized way. *Paarlberg et al.* [2005] applied this concept to river dunes and propose a parameterization of the flow separation zone, based on flow measurements reported in literature in the separation zones in laboratory flumes.

4. Marine Sand Waves

[19] Accurate observations are indispensable for studying migration of sand waves. Until now, accurate information on migration rates was rare, due to offset problems in offshore measurements, in combination with expected slow migration rates (meters per year). Recent progress on techniques to estimate sand wave migration using spatial cross-correlation techniques is reported by *Duffy and Hughes-Clarke* [2005]. *Dorst* [2004] developed a statistical method to detect dynamics (variations) in sand waves over time that allows measurements inaccuracies to be taken into account. It is now possible to detect migrations and to determine migration rates. *van Dijk and Kleinhans* [2005] show migration rates (including accuracies) at four sites in the North Sea, being all in the order of 5 m per year. These authors report local variations together with other physical characteristics that enable comparison of these observations with theoretical results of *Németh et al.* [2002] and *Besio et al.* [2004]; that is, they suggest that residual currents or tidal asymmetry may explain these variations. *Knaapen* [2005] developed an empirical formula to estimate sand wave migration rate, based solely on the shape of the sand wave. He used the underlying idea that the mechanisms behind creation of asymmetry and migration have similar origins. Theoretical proof for this result is still to be found.

[20] *Bartholdy et al.* [2005] report that relationships between dune dimensions and grain size, as established in previous studies, can be generalized further. *Van der Veen et al.* [2005] investigated the role of physical parameters, describing flow and sediment, in the generation of sand waves and found that sand wave occurrence in the North Sea can be better explained if the local grain sizes are included.

[21] The origin of sand waves was first explained by *Hulscher* [1996] using a linear stability analysis in a coupled tide-erodable bed system. The vertical dimension of the flow turned out to be crucial to make (tidally averaged) vertical vortices grow, favoring sand wave development. The characteristics of fully evolved sand waves were given by *Komarova and Newel* [2000] using a weakly nonlinear theory. On the basis of and validated by the linear stability theory [*Németh*, 2003], the intermediate development (growth) of sand waves is now simulated in a numerical model [*Németh et al.*, 2005]. *Németh* [2003] found that the timescale of sand wave growth is about 5–10 years. They also showed that estimates of sand wave migration rate based on the linear stability theory deviates less than 10% from the nonlinear predictions. *Klein and Schuttelaars* [2005] present a combination of a complicated process-based nearshore model and mechanism-oriented analysis techniques to explain nearshore morphodynamics. Sand wave modelers hope to apply similar techniques to improve

our understanding of sand wave evolution in less idealized settings offshore (e.g., including wind waves). *Roos et al.* [2005] found that the process of spatial development and spreading of sand waves can be understood and well approximated using a simplified model.

[22] Sand waves seldom appear in isolation. Sand waves often appear with megaripples [e.g., *Passchier and Kleinhans*, 2005]. *Passchier and Kleinhans* [2005] also analyzed occurrence of 2-D and 3-D features offshore. A possible explanation of the link between megaripples and sand waves is given by the bed roughness. The generation mechanism is the same; due to increases in roughness the most favorable wavelength shifts from the sand wave regime to shorter bed waves [*Idier et al.*, 2004]. A laboratory study by *Marin et al.* [2005] suggests that solitary waves can also create sand-wave-like features, on which ripples are superimposed. Verification of this mechanism in the field is still a challenge.

5. Sand Wave and River Dune Processes in the Context of Related Features

[23] Sand waves and river dunes develop due to a positive feedback between flow and a sandy bottom. This so-called ''morphodynamic system'' consists of three interrelated parts: flow, sediment transport and continuity of sediment. The latter leads to changes in bed topography at locations where divergences and convergences in sediment transport occur.

[24] Usually, morphodynamic patterns evolve on a much longer timescale than that of the flow, e.g., sand waves develop in months to years, whereas the M2 tidal motion period is about 12 hours. This encourages an integrated, time-averaged approach to obtain understanding in the pattern evolution (in terms of self-organization on the pattern level), rather than a bottom-up approach focusing on a detailed description of the separate processes in flow and sediment transport. Still, improved and detailed understanding of sediment transport and flow is needed to improve understanding of pattern evolution. For instance, recent progress in understanding the occurrence of vertical grading of sediment mixtures in river dunes and the development of an armoring layer has clear consequences for long-term behavior of river dunes [*Blom et al.*, 2003]. Also, improved modeling of sediment transport, e.g., over seabed ripples or as sheet flow, will possibly contribute to a quantitatively more realistic evolution of sand waves. Typical techniques used to study the self-organization process directly are stability analyses (see, e.g., *Hulscher* [1996] for sand waves and tidal sand banks) agent-based modeling (as cellular automata) and direct numerical simulations. The latter two are utilized in modeling of aeolian dunes.

[25] Related to the water-sediment systems are systems in which sediment and air interact, resulting in the development of aeolian dunes. *Werner* [1995] introduced a cellular automata type of sediment transport model to describe the formation of different types of dunes in terms of emergent patterns in complex, dynamical systems. *Stam* [1997] developed kinematical, analytical and numerical models to describe aeolian dunes, all based on a description of the physical processes that form the dunes. Recently, *Parsons et al.* [2005] used computational fluid dynamics to describe the full process of aeolian dune formation, employing a k-epsilon turbulence model. The turbulence model was parameterized by *Kroy et al.* [2002]. A second example of a related system is the system of blue ice and air, on which ice ripples develop [*Bintanja et al.*, 2001]. In this system, the amount of ice is not conserved, which makes the modeling slightly different. However, in both related examples shear between the two media is the forcing leading to local deformations in the slowest one, and thus to pattern formation in this medium. Research on pattern formation itself has strong attention of mathematicians and physicists [see, e.g., *Bowman and Newell*, 1998].

6. Conclusions and Future Challenges

[26] Having reported the contributions to the sand wave and river dune science, it is clear that there remain many open ends. For instance, details of the connection of turbulent flow with either sand waves or river dunes are still under investigation. Steps forward can only be made if insights from several disciplines (civil engineering, physics, physical geography, geology, mathematics, geodesy, etc.) are connected. We really have to stand on our toes to understand each other, which makes this a very interesting, interdisciplinary field. Finally, we will increasingly need this knowledge, as we have to be able to forecast both natural impacts and human interventions in sandy bed rivers and coastal seas. In many cases, these beds are covered with large prominent sand waves or dunes.

[27] Given the present knowledge of marine sand wave and river dune dynamics and the practical relevance of understanding these phenomena, we see the following challenges for the future.

[28] 1. One challenge is to unravel the relation between the dimensions of these bed forms, the corresponding hydraulic roughness and the influence on water levels. Important aspects to consider here are (1) the effects of extreme situations that have not occurred but must be used as design conditions in engineering practice, (2) the delayed response of river dunes to changing discharges and the influence of this on the dynamics of the hydraulic roughness, (3) effects of composition of the bed sediment and layering of the bed, (4) effects of composite bed forms (i.e., smaller bed forms superimposed on larger ones, and (5) the link between offshore bed forms (e.g., sand waves) and a locally estimated hydraulic roughness in order to improve model predictions of water levels and velocities offshore and along the coastline.

[29] 2. A second challenge is to identify and quantify the uncertainties related to marine sand waves and river dunes, i.e., both the uncertainties in the models that describe or predict these bed forms, as well as the uncertainties in the data, and to understand the effects of these uncertainties in order to interpret model results and observations adequately.

[30] 3. A third challenge is to understand the differences between marine sand waves and river dunes and between these bed forms and those of different spatial scales. Related to this is understanding why bed forms with different spatial scales can occur simultaneously, at the same location.

[31] 4. Another challenge is using the knowledge of generation and development of bed forms to understand and quantify the effects of human interventions in the natural system, e.g., the morphological development of the seabed due to a sand mining pit or the morphological development of the river bed after dredging of a navigation channel.

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References

Allen, J. R. L. (1978), Computational methods for dune time-lag: Calculations using Stein's rule for dune height, *Sediment. Geol.*, *20*(3), 165–216.

Amsler, M. L., and M. H. García (1997), Sand-dune geometry of large rivers during floods: Discussion, *J. Hydraul. Eng.*, *123*, 582–584.

Amsler, M. L., and M. I. Schreider (1999), Dune height prediction at floods in the Paraná River, Argentina, in *River Sedimentation: Theory and Applications*, edited by A. W. Jayewardena, J. H. W. Lee, and Z. Y. Wang, pp. 615–620, A. A. Balkema, Brookfield, Vt.

Bagnold, R. A. (1941), *The Physics of Blown Sand and Desert Dunes*, CRC Press, Boca Raton, Fla.

Bartholdy, J., B. W. Flemming, A. Bartholomä, and V. B. Ernstsen (2005), Flow and grain size control of depth-independent simple subaqueous dunes, *J. Geophys. Res.*, *110*, F04S16, doi:10.1029/2004JF000183.

Besio, G., P. Blondeaux, M. Brocchini, and G. Vittori (2004), On the modeling of sand wave migration, *J. Geophys. Res.*, *109*, C04018, doi:10.1029/2002JC001622.

Best, J. L. (2005), Fluid dynamics of river dunes: A review and some future research directions, *J. Geophys. Res.*, doi:10.1029/2004JF000218, in press.

Bintanja, R., C. H. Reijmer, and S. J. M. H. Hulscher (2001), Detailed observations of the rippled surface of Antarctic blue ice areas, *J. Glaciol.*, *47*(158), 387–396.

Blom, A., J. S. Ribberink, and H. J. de Vriend (2003), Vertical sorting in bed forms: Flume experiments with a natural and a trimodal sediment mixture, *Water Resour. Res.*, *39*(2), 1025, doi:10.1029/2001WR001088.

Bowman, C., and A. C. Newell (1998), Natural patterns and wavelets, *Rev. Mod. Phys.*, *70*(1), 289–301.

Carling, P. A., K. Richardson, and H. Ikeda (2005), A flume experiment on the development of subaqueous fine-gravel dunes from a lower-stage plane bed, *J. Geophys. Res.*, *110*, F04S05, doi:10.1029/2004JF000205.

Dorst, L. L. (2004), Survey plan improvement by detecting sea floor dynamics in archived echo sounder surveys, *Int. Hydrogr. Rev.*, *5*(2), 49–63.

Duffy, G. P., and J. E. Hughes-Clarke (2005), Application of spatial cross correlation to detection of migration of submarine sand dunes, *J. Geophys. Res.*, *110*, F04S12, doi:10.1029/2004JF000192.

Engelund, F. (1970), Instability of erodible beds, *J. Fluid Mech.*, *42*, 225–244.

Ernstsen, V. B., R. Noormets, C. Winter, D. Hebbeln, A. Bartholomä, B. W. Flemming, and J. Bartholdy (2005), Development of subaqueous barchanoid-shaped dunes due to lateral grain size variability in a tidal inlet channel of the Danish Wadden Sea, *J. Geophys. Res.*, *110*, F04S08, doi:10.1029/2004JF000180.

Fredsøe, J. (1974), On the development of dunes in erodible channels, *J. Fluid Mech.*, *64*, 1–16.

Haitel, L., and C. M. Dohmen-Janssen (2005), Climate change and navigation: The effects of Rhine river dunes on channel depth, *Hydro Int.*, *9*(6), 31–33.

Hersen, P. (2005), Flow effects on the morphology and dynamics of aeolian and subaqueous barchan dunes, *J. Geophys. Res.*, *110*, F04S07, doi:10.1029/2004JF000185.

Hulscher, S. J. M. H. (1996), Tidal-induced large-scale regular bed form patterns in a three-dimensional shallow water model, *J. Geophys. Res.*, *101*(C9), 20,727–20,744.

Idier, D., D. Astruc, and S. J. M. H. Hulscher (2004), Influence of the bed roughness on dune and megaripple generation, *Geophys. Res. Lett.*, *31*, L13214, doi:10.1029/2004GL019969.

Kennedy, J. F. (1963), The mechanics of dunes and antidunes in erodible-bed channels, *J. Fluid Mech.*, *16*, 521–544.

Klein, M. D., and H. M. Schuttelaars (2005), Morphodynamic instabilities of planar beaches: Sensitivity to parameter values and process formulations, *J. Geophys. Res.*, *110*, F04S18, doi:10.1029/2004JF000213.

Kleinhans, M. G. (2005), Upstream sediment input effects on experimental dune trough scour in sediment mixtures, *J. Geophys. Res.*, *110*, F04S06, doi:10.1029/2004JF000169.

Knaapen, M. A. F. (2005), Sandwave migration predictor based on shape information, *J. Geophys. Res.*, *110*, F04S11, doi:10.1029/2004JF000195.

Knaapen, M. A. F., and S. J. M. H. Hulscher (2002), Regeneration of sand waves after dredging, *Coastal Eng.*, *46*(4), 277–289.

Komarova, N. L., and A. C. Newell (2000), Nonlinear dynamics of sand banks and sand waves, *J. Fluid Mech.*, *415*, 285–312.

Kostaschuk, R., and J. Best (2005), Response of sand dunes to variations in tidal flow: Fraser Estuary, Canada, *J. Geophys. Res.*, *110*, F04S04, doi:10.1029/2004JF000176.

Kroy, K., G. Sauermann, and H. J. Herrmann (2002), Minimal model for aeolian sand dunes, *Phys. Rev. E*, *66*(3), 31302, doi:10.1103/PhysRevE.66.031302.

Langlois, V., and A. Valance (2005), Three-dimensionality of sand ripples under steady laminar shear flow, *J. Geophys. Res.*, *110*, F04S09, doi:10.1029/2004JF000278.

Marin, F., N. Abcha, J. Brossard, and A. B. Ezersky (2005), Laboratory study of sand bed forms induced by solitary waves in shallow water, *J. Geophys. Res.*, *110*, F04S17, doi:10.1029/2004JF000184.

Németh, A. A. (2003), Modelling offshore sand waves, Ph.D. thesis, 140 pp., Univ. of Twente, Enschede, Netherlands.

Németh, A. A., S. J. M. H. Hulscher, and H. J. de Vriend (2002), Modelling sand wave migration in shallow shelf seas, *Cont. Shelf Res.*, *22*(18-19), 2795–2806.

Németh, A. A., S. J. M. H. Hulscher, and H. J. de Vriend (2003), Offshore sand wave dynamics, engineering problems and future solutions, *Pipeline Gas J.*, *230*(4), 67–69.

Németh, A. A., S. J. M. H. Hulscher, and R. M. J. van Damme (2005), A sand wave simulation model, *Coastal Eng.*, in press.

Niño, Y., A. Atala, M. Barahona, and D. Aracena (2002), Discrete particle model for analyzing bed form development, *J. Hydraul. Eng.*, *128*(4), 381–389.

Paarlberg, A. J., C. M. Dohmen-Janssen, S. J. M. H. Hulscher, and A. P. P. Termes (2005), A parametrization for flow separation in a river dune development model, in *Proceedings of the 4th IAHR Symposium on River, Coastal and Estuarine Morphodynamics, 4–7 Oct 2005, Urbana, USA*, edited by G. Parker and M. Garcia, pp. 883–895, Taylor and Francis, Philadelphia, Pa.

Parsons, D. R., J. L. Best, O. Orfeo, R. J. Hardy, R. Kostaschuk, and S. N. Lane (2005), Morphology and flow fields of three-dimensional dunes, Rio Paraná, Argentina: Results from simultaneous multibeam echo sounding and acoustic Doppler current profiling, *J. Geophys. Res.*, doi:10.1029/2004JF000231, in press.

Passchier, S., and M. G. Kleinhans (2005), Observations of sand waves, megaripples, and hummocks in the Dutch coastal area and their relation to currents and combined flow conditions, *J. Geophys. Res.*, doi:10.1029/2004JF000215, in press.

Pekeris, C., and B. Shkoller (1967), Stability of plane Poiseuille flow to periodic disturbances of finite amplitude in the vicinity of the neutral curve, *J. Fluid Mech.*, *29*, 31–38.

Roos, P. C., P. Blondeaux, S. J. M. H. Hulscher, and G. Vittori (2005), Linear evolution of sandwave packets, *J. Geophys. Res.*, *110*, F04S14, doi:10.1029/2004JF000196.

Stam, J. M. T. (1997), On the modelling of two-dimensional aeolian dunes, *Sedimentology*, *44*(1), 127–141.

Stansby, P. K., and J. G. Zhou (1998), Shallow water flow solver with non-hydrostatic pressure: 2D vertical plane problems, *Int. J. Numer. Methods Fluids*, *28*(3), 541–563.

Ten Brinke, W. B. M., A. W. E. Wilbers, and C. Wesseling (1999), Dune growth, decay and migration rates during a large-magnitude flood at a sand and mixed sand-gravel bed in the Dutch Rhine river system, in *Fluvial Sedimentology VI*, edited by N. Smith and J. Rogers, *Spec. Publ. Int. Assoc. Sedimentol.*, *28*, 15–32.

van Dijk, T. A. G. P., and M. G. Kleinhans (2005), Processes controlling the dynamics of compound sand waves in the North Sea, Netherlands, *J. Geophys. Res.*, *110*, F04S10, doi:10.1029/2004JF000173.

Van der Veen, H. H., S. J. M. H. Hulscher, and M. A. F. Knaapen (2005), Grain-size dependency in the occurrence of sand waves, *Ocean Dyn.*, in press.

Van Rijn, L. C. (1984), Sediment transport, part III: Bed forms and alluvial roughness, *J. Hydraul. Eng.*, *110*(12), 1733–1754.

Watanabe, Y., M. Tubino, G. Zolezzi, and K. Hoshi (2001), Behaviour of alternate bars under unsteady flow conditions, in *2nd IAHR Symposium On River, Coastal and Estuary Morphodynamics, Obihiro, Japan*, edited by S. Ikeda, pp. 673–682, Hokkaido Univ. Press, Sapporo, Japan.

Werner, B. T. (1995), Eolian dunes—Computer simulations and attractor interpretation, *Geology*, *23*(12), 1107–1110.

Yalin, M. S. (1964), Geometrical properties of sand waves, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, *90*(5), 105–119.

Yamaguchi, S., and N. Izumi (2002), Weakly nonlinear stability analysis of dune formation, in *Proceedings River Flow 2002*, edited by D. Bousmar and Y. Zech, pp. 843–850, Swets and Zeitlinger, Lisse, Netherlands.

Yoon, J. Y., and V. C. Patel (1996), Numerical model of turbulent flow over sand dune, *J. Hydraul. Eng.*, *122*(1), 10–18.

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