Initiation and growth of fluvial dunes

S. E. Coleman
Department of Civil and Environmental Engineering, The University of Auckland, Auckland, NZ
V. I. Nikora
School of Engineering, The University of Aberdeen, Aberdeen, Scotland, UK

ABSTRACT: Fluvial dunes are striking in their apparent order, and mysterious in their origin and how they achieve their purpose. Advances in experimental equipment and computing capacity are stimulating investigations of dunes that are of increasing detail and insight. In the following, the initiation and growth of fluvial dunes is discussed, along with the importance of recognising process scales in measurements and analyses. A brief overview of some of the present challenges faced in regard to fluvial dune dynamics concludes the paper.

1 INTRODUCTION

Wherever one looks, granular surfaces formed by fluids are patterned. For riverbeds, the organised patterns cover a wide range of scales, from granular patches, to ripples, dunes, bars, and meanders. These varied bedforms are studied in many fields, including geology, geography, hydrology, and engineering. Analyses furthermore range from fundamental analytical descriptions, to detailed numerical simulations and laboratory measurements, to large-scale field measurements. Part of the attraction to study these phenomena lies in the mystery of how trains of highly-ordered sediment waves can arise from the chaos of the underlying turbulence and grain-motion dynamics. The patterns themselves are also captivating, luring researchers into attempts to quantify the apparent structures. More pragmatically, understanding of these bedforms is required in regard to interpretation of stratigraphic records, as well as analysis and management of both near-bed habitats and also transport of sediments and attached micro-organisms and chemicals (e.g. nutrients, contaminants).

The focus of this paper is river-dune initiation and growth, including underlying bed, flow and sediment dynamics. The following section discusses process scales, including interpretation of collected data such as the experimental measurements providing the background to the paper. Dune initiation and development are then discussed. The paper concludes with a brief overview of some contemporary challenges faced in regard to fluvial dune dynamics.

2 PROCESS SCALES AND INTERPRETATION

Studies of velocity and stress fields controlling or associated with dunes have typically considered steady-state bedform magnitudes. Recent intense focus on the simplified case of flow over fixed asymmetrical dunes includes the works of van Mierlo and de Ruiter (1988), Lyn (1993), Nelson et al. (1993), McLean et al. (1994, 1999), Nelson et al. (1995), Bennett and Best (1995), Kadota and Nezu (1999), Venditti and Bennett (2000), Cellino and Graf (2000) and Maddux et al. (2003a,b). These studies, and others (e.g. McLean 1990, Kleinhans 2004, Best 2005a), highlight that dominant features of flow over a dune include (Fig. 1): a separating shear layer (with internal recirculation but also active mixing with the outer flow) in the lee of the dune crest, reattachment of the separated flow to the bed approximately 4-6 dune heights downstream of the crest, and development of an internal boundary layer along the dune stoss slope (with the near-bed turbulence in this region differing markedly from either classical boundary-layer or wake turbulence, ASCE 2002).

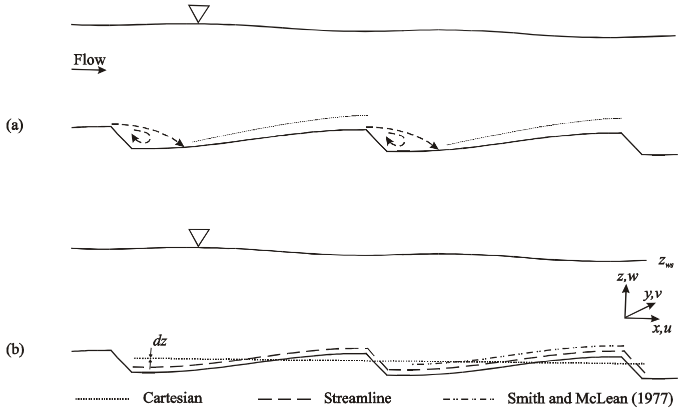

Figure 1. Flow over dunes: a) schematic of dominant flow features, b) co-ordinate definitions and schematic of spatial-averaging approaches.

Contemporary advances in experimental equipment and computing capacity have enabled measurements and simulations of this flow structure and sediment transport over dunes at increasingly finer temporal and spatial resolutions (e.g. Hyun et al. 2003; Best 2005b; Yue et al. 2005,2006; Clunie et al. 2007; Stoesser et al. 2008; McLean et al. 2008a). The resulting detailed insight into the physical processes is interesting and valuable in itself. Particularly for those involved in the design and management of fluvial pathways, however, the challenge is to interpret the collected data in terms of how the observed fine-scale turbulent structures (e.g. Fig. 1), bed-level variations and grain motions contribute to bulk bed, flow and transport characteristics, such as hydraulic resistance, bed shear stress, and sediment transport rate (e.g. ASCE 2002). In this regard, if the bed roughness is described in an averaged sense, e.g. mean dune wavelength, associated descriptions of flow and sediment-transport properties should be representative of this spatial domain, i.e. scale-consistent, which typically will require spatial averaging of measured flow and transport data.

Smith and McLean (1977) provide one of the first attempts at spatial averaging flow over dunes. For a variety of reasons, they averaged data along lines parallel to the bed surface, and only averaged over the upward-sloping stoss region of the dune (Fig. 1). An alternative approach of averaging equations of motion and data along lines of constant Cartesian coordinates (Fig. 1) has been shown to provide a rigorous framework for data analysis and insight into physical processes for flows over rough beds (e.g. Wilson and Shaw 1977; Raupach et al. 1991; Giménez-Curto and Corniero Lera 1996; Finnigan 2000; López and García 2001; Nikora et al. 2001, 2007a,b). For slowly-varying (relative to the flow) dune heights, instantaneous flow and sediment properties can be decomposed in this second approach as

$$u_i = \bar{u}_i + u_i' = \langle \bar{u}_i \rangle + \tilde{u}_i + u_i' \qquad \langle \bar{u}_i \rangle = \frac{1}{V_f} \iiint_{V_f} \bar{u}_i \, dV \qquad (1)$$

where (Fig. 1) u_i is the i-th component, in direction $x_i = (x, y, z)$, of the instantaneous velocity vector (u, v, w); the straight overbar and angled brackets represent averaging in time (over the period of dune-height invariance) and space respectively; $\langle \bar{u}_i \rangle$ is double-averaged (in time and space) velocity; $\tilde{u}_i$ is the spatial fluctuation in the time-averaged velocity; $\langle \tilde{u}_i \rangle$ = 0; u_i' is the temporal (turbulent) velocity fluctuation; and V_f = volume occupied by fluid within the total averaging volume V_o. For dunes, the spatial-averaging volume V_o is defined as a thin slab (of thickness dz) parallel to the mean bed slope (Fig. 1), whose lateral extent encompasses the ranges of longitudinal and transverse bedform lengths. At levels above the highest dune crest, $V_f = V_o$ and spatial averaging is straightforward. Below crests, $V_f < V_o$ and the averaging volume is only partially filled with fluid.

Utilising the decomposition of (1), interactions between the bed, flow and sediment transport can then be investigated at a primary level based on double-averaged properties. To this end, the Navier-Stokes equations can be averaged in time and space to identify key momentum transfer processes for dunes (e.g. Nikora et al. 2007a,b). For steady high-Reynolds number water flows over slowly-varying (relative to the flow) dunes, the double-averaged momentum conservation equation for the longitudinal velocity $u_i = u$ can be presented in a vertically-integral form (simply summing thin bed-parallel spatial-averaging slabs, Nikora et al. 2007a,b, Coleman et al 2008a) as

$$gS_b \int_z^{z_{ws}} \phi \, dz = \int_z^{z_{ws}} \left[\phi \langle \bar{u}_j \rangle \frac{\partial \langle \bar{u} \rangle}{\partial x_j} + \frac{1}{\rho} \frac{\partial \phi \langle \bar{p} \rangle}{\partial x} - \frac{\partial \phi \langle \tau_{1j} \rangle / \rho}{\partial x_j} \right] dz - \int_z^{z_c} \frac{1}{V_o} \iint_{S_{\text{int}}} \left[\frac{\bar{p}}{\rho} n_x - \nu \frac{\partial \bar{u}}{\partial x_j} n_j \right] dS \, dz \qquad (2)$$

where g is gravitational acceleration; S_b is mean bed slope; z_{ws} is the water-surface level; $\phi = V_f/V_o$ is the roughness geometry function ($1 \geq \phi \geq 0$); ρ = fluid density; p is point pressure; z_c is the uppermost (crest) level of the bed; S_{int} is the surface area of roughness-fluid interface within the thin-slab averaging volume; n_i is the i^{th} component of the unit vector normal to the surface element dS and directed into the fluid; ν =fluid kinematic viscosity; the boundary resistance forces exist for $z \leq z_c$; the Einstein convention is adopted, which prescribes a summation over each repeated index; and the right-handed coordinate system is implied (Fig. 1), i.e., the x-axis (u velocity component) is oriented along the main flow parallel to the averaged bed slope, the y-axis (v velocity component) is oriented to the left bank, and the z-axis (w velocity component) is pointing towards the water surface. The fluid stresses $\langle \tau_{1j} \rangle = -\rho \left(\langle \overline{u'u_j'} \rangle + \langle \tilde{u}\tilde{u}_j \rangle \right)$, where viscous fluid stresses can be neglected for the high-Reynolds number water flows, $-\rho\langle\overline{u'u'_j}\rangle$ are spatially-averaged Reynolds stresses, and $-\rho\langle\tilde{u}\tilde{u}_j\rangle$ are form-induced (dispersive) stresses that are analogous to Reynolds stresses but due to correlations of spatial variations rather than temporal fluctuations. The roughness geometry function ϕ, which varies from unity above the roughness crests ($z > z_c$) to a minimum within the channel bed, is a statistical measure of both the random geometry of the bed surface and the porosity, becoming analogous to the conventional porosity coefficient when evaluated below the lowest trough level. Equation (2) can be seen to describe the flux of gravity-induced momentum (left-hand side of (2)) via spatially-averaged fluid stresses $\langle\tau_{1j}\rangle$, secondary currents and flow nonuniformity to the boundary, where the momentum is removed through form drag and skin friction (last two terms of (2)). Development of the respective double-averaged equations for transport of fluid momentum, passive substances, and suspended sediments are outlined further in Nikora et al. (2007a,b), where these equations explicitly include appropriate form-induced fluxes and source/ sink terms.

Spatial averaging is particularly valuable for describing and analyzing flows over sand-waves, including offering better definitions for flow uniformity, flow two-dimensionality, and bed shear stress (e.g. Nikora et al., 2007a), as well as providing improved insight into momentum flux components and balance as outlined above. In contrast to the double averaging (in time and space) discussed above, appropriate flow decompositions, averaging and governing equations for rapidly-varying beds are discussed in Clunie et al. (2007), Coleman and Nikora (2008a) and Coleman et al. (2008b). The first of these papers presents the design and interpretation of a flying-probe methodology allowing measurements of fluctuating fields of large spatial extent. This methodology was developed and utilised in a multi-year New-Zealand-government-funded project to advance understanding of subaqueous sand waves (Coleman et al. 2008a). The advantages of scale recognition and appropriate averaging of equations and measurements in the related fields of coastal bedforms and particle entrainment are highlighted in Coleman et al. (2008b) and Coleman and Nikora (2008a) respectively. In the following analyses of dune initiation, spatial averaging of flow properties is not required, with bed roughnesses of the order of the grain size and the measurement resolution. For the subsequent analyses of dune development discussed herein, double-averaging is adopted, where the bed was fixed at successive stages of development in order to facilitate the time averaging undertaken.

3 DUNE INITIATION

The generation of dunes from plane-bed conditions is typically attributed to one of three phenomena: a) turbulent fluid motions, e.g. Velikanov (1955), Kondrat'ev et al. (1959), Jackson (1976), and Yalin (1992); b) instability of the fluid-sediment flow system when perturbed, e.g. Liu (1957), Kennedy (1969), Gradowczyk (1970), Engelund (1970), Smith (1970), Fredsøe (1974), Richards (1980), Colombini (2004), Zhou and Mendoza (2005), and Venditti et al. (2006); and c) granular transport mechanics, e.g. Raudkivi (1966), Langbein and Leopold (1968), Smith (1970), McLean and Smith (1986), Niño et al (2002), and Venditti et al. (2005). It is clear that a wide spectrum of theories exists for the generation of dunes, with all of these theories still challenged by unresolved inconsistencies. In this regard, it is of interest to note that PIV-measured near-bed streamwise- and vertical-velocity autospectra for the mobile-sediment beds of Coleman and Nikora (2008b) showed no dominant periodicities, where energies in selected wavenumbers would be expected for wavelet generation arising from flow instabilities or organised turbulent structures.

Based on measurements of bed profiles and bed and flow dynamics leading to dune generation (e.g. Coleman and Melville 1996, Coleman and Eling 2000, Coleman et al. 2003, and the PIV-based analyses of Coleman and Nikora 2008b), the writers conjecture that the highly-regular seed wavelets from which both ripples and dunes develop are generated in a two-stage process. The first stage involves interacting random patches of sediment of varying lengths (principally 7-15d, where d is sediment size) that are present on planar mobile alluvial beds (Coleman and Nikora 2008b). These patches reflect the passage of bed disturbances that are caused by attached eddies. The eddy-generated bed disturbances propagate at speeds that are proportional to their size, with average speeds that are less than overhead eddy convection velocities, but potentially larger than local average fluid and sediment velocities (Fig. 2). When interactions of the moving patches result in a bed disturbance that exceeds a critical height (H_c) and interrupts the bed-load layer, i.e. $H_c \approx$ 3-4d, mass conservation dictates that the disturbance will accumulate sediment. Regular organised wavelets will then be generated successively downstream of the stabilised disturbance via a scour-deposition wave (e.g. Raudkivi 1966, Smith 1970, Fredsøe 1986, McLean and Smith 1986). This second stage of the wavelet-generation process arises from sediment-continuity requirements and the bed-stress distribution downstream of a bed perturbation, which peaks at a distance of λ/H_c = O(30-40).

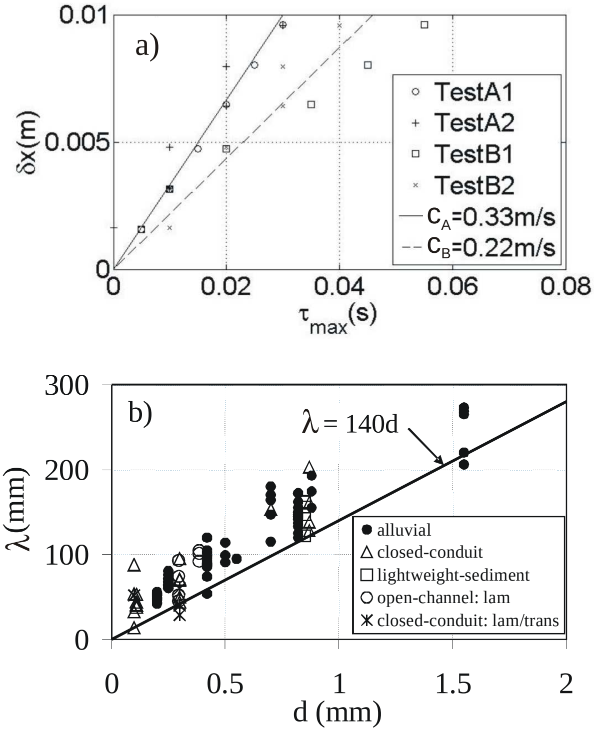

Figure 2 Dune initiation: a) bed-disturbance speeds *c* from maxima in bed-level space-time correlations (uniform sediment of d = 0.8mm and specific gravity s = 2.65, with near-bed $\langle \overline{u} \rangle$ = 0.27 and 0.22 m/s and near-bed eddy convection velocity u_e = 0.38 and 0.32 m/s for Series "A" and "B" flows respectively, Coleman and Nikora 2008b), b) wavelet length λ as a function of sediment size *d*.

The above generation process gives organised wavelets of preferred lengths of $\lambda/d = (\lambda/H_c)(H_c/d)$ = O(120). Previous empirical equations based on measured bed profiles that predict the scaling of wavelet length with grain diameter, $\lambda \propto d^{\alpha}$, are of α = 0.74 (Coleman 1991; Coleman and Melville 1996), α = 0.5 (Raudkivi 1997), and α = 0.75 (Coleman and Eling 2000). If it is recognised that the bed-profile measurements at 15+s intervals may have allowed some sand-wave growth prior to identification of the initial wavelengths (Fig. 2), then a lower bound to the measurements of Fig. 2 of λ/d = 120-140 can be adopted to better describe sand-wavelet lengths. This result provides a reasonable approximation to the concept-based prediction of scaling.

The identified two-stage generation mechanism is valid for fully-turbulent hydraulically-smooth and rough-bed flows of small to large sediment transport rates, where wavelets can be propagated downstream almost "instantaneously" for general sediment transport. It explains the observed similar scaling (e.g. Coleman et al. 2003) of alluvial, closed-conduit and lightweight-sediment wavelets (Fig. 2), and also the generation of wavelets on the stoss slopes of larger bedforms. It is also valid (e.g. Coleman and Eling 2000) for open-channel and closed-conduit laminar flows (Fig. 2), although the critical disturbances leading to wavelet generation arise through bed discontinuities, and not turbulence-based bed disturbances.

4 DUNE DEVELOPMENT

Once wavelets have been generated, their heights increase through sediment continuity and the sediment-trapping nature of the bedform lee region. Wavelet lengths concomitantly increase with heights, although initially at slower rates, principally due to the downstream bed-stress distribution scaling. As the waves grow still larger, continuity requires coalescence of the growing sand waves. This arises with smaller faster waves approaching and merging with larger slower waves (e.g. Raudkivi and Witte 1990, Ditchfield and Best 1992, McLean 1990, Coleman and Melville 1994). Which of the bedforms will be selected in a given instance of coalescence depends upon the local bed-form spacing requirements appropriate to the particular event, with these requirements in turn governed by the interaction between the local bed structure and associated flow patterns. Flow-system-instability-generated periods of accelerated growth occurring as dunes develop (e.g. Coleman and Fenton 2000) are typically paralleled by increases in the number of bed-form coalescences occurring, with multiple successive bed-form coalescences occurring at the appropriate stages of the bed development (Coleman and Melville, 1994). The growing and cascading (e.g. Jain and Kennedy 1974) bed-level variance as dunes grow gives larger spectral levels at increasingly lower wave numbers, with a wavenumber spectral scaling of "-3" for the self-similar sand waves, until equilibrium sand-wave magnitudes are achieved (e.g. Hino 1968, Nakagawa and Tsujimoto 1984, Nikora et al. 1997).

Overall, sediment-wave growth from plane-bed conditions can be described by the power law $(P/P_{ss}) = (t/t_{ss})^{\gamma}$, where P is the average value of a sediment-wave parameter (length λ or height h) after time t, t_{ss} is the time to achieve steady-state magnitude P_{ss}, and γ is a growth exponent (e.g. Grinvald and Nikora 1988, Nikora and Hicks 1997, Coleman et al. 2005). Based on a series of six experiments of two sediment sizes, Nikora and Hicks (1997) proposed $\gamma = 0.28$ for both heights and lengths, implying invariant bedform steepness (over $0.01 < t/t_{ss} < 1$) for the developing bedforms. For a greater number of experiments of wider ranges of flows and sediments, Coleman et al. (2005) found average values of $\gamma_\lambda = 0.32$ and γ_h = 0.37 for bed-form lengths and heights, respectively. These results of $h/\lambda \propto t^{(\gamma_h - \gamma_\lambda)} \propto t^{0.05}$ imply a very rapid initial growth in bed-form steepness to a value that is approximately maintained over the major period of bed-form growth.

Recognising that dune steepness (and thereby dune geometric similarity) can be taken to be essentially invariant during the major period of growth, Coleman et al. (2006) undertook a series of experiments whereby flow fields, bed pressures and water-surface levels were measured at various stages of two-dimensional (2D) dune development from plane-bed conditions for the same steady uniform 2D flow. The measured development stages were of t/t_{ss} = 0.13-0.16, 0.27-0.34, 0.43-0.56, and 0.78-1, respectively. The experimental results highlight that the flow structure within the roughness-layer (comprising the near-bed interfacial and form-induced layers, Nikora et al. 2001, 2007b) is of negligible variation as 2D dunes develop. This finding was noted in terms of normalised spatial fields of time-averaged velocities and stresses, and normalised vertical distributions of double-averaged (in time and space) longitudinal velocity, double-averaged normal stresses, and the components of the double-averaged momentum balance for the flow. These results reveal the equilibrium (self-similar) nature of the near-bed boundary layer over developing 2D dunes with flow separation in the dune lee.

The above experiments showed a number of additional results of interest for the 2D dunes (Coleman et al. 2006, 2008a), including: a) the linear nature of the double-averaged longitudinal-velocity distribution (e.g. Nikora et al. 2004, McLean and Nikora 2006, McLean et al. 2008b) below the crests of developing dunes; b) invariance of the normalised bed-stress profile along dunes as these grow; c) increases in double-averaged Reynolds stress in the vicinity of the dune crest being balanced by equivalent negative form-induced stresses at these levels; and d) invariance with dune growth of the relative contributions of each of Reynolds stress, form-induced stress, skin friction and form drag to the overall momentum-flux balance, with the sum of these components balancing the streamwise component of the weight of the fluid volume as per (2). In general, double-averaged interfacial-layer longitudinal-velocity distributions vary from exponential to linear to logarithmic with increasing roughness-element spacing (e.g. Nikora et al. 2004, Coleman et al. 2007a), with a linear distribution appropriate for the tested developing 2D dunes of steepness h/λ = 1/18.75. The measurements of bed pressures with overhead flow velocities for these and other experiments further enabled expressions to be derived for drag coefficient $C_D = f(z)$ for a range of dune steepnesses (Coleman et al. 2007b).

5 SOME CONTEMPORARY CHALLENGES

Present research efforts in regard to fluvial dunes vary significantly in scale, approach and focus. The discussions above concentrate on the details of bed, sediment and flow dynamics as dunes are initiated and grow. To conclude the paper, we provide a brief comment on some key areas related to river dunes that require further research. Our list is not meant to be exhaustive, but rather it is intended to complement other recent reviews of research needs and directions (e.g. ASCE 2002, Best 2005a), and to highlight some particular research aspects that we have identified in our endeavours.

At a fundamental level, work still remains to determine the principal parameters that adequately characterise a dune field (e.g. representative length, height, width, shape factors, etc.). In this regard, means to mechanistically and objectively quantify the three-dimensionality of dunes are particularly required, e.g. in order to appropriately link bed topography with flow resistance (Sirovich and Karlsson 1997; Maddux et al. 2003a,b; Venditti 2007; Best 2005a), especially for mobile bed waves that vary markedly in space and time. Related to dune-characterisation, further work is required to address the strong debates that continue in the hydraulics and earth-sciences communities as to the natures and mechanics of, and differences between, ripples and dunes. Such studies will contribute to improved means of predicting the occurrence in nature of these respective bedforms. Additional research is also needed in regard to general relations predicting bedform speeds as functions of flow conditions, sediments, and bedform magnitudes (e.g. Raudkivi 1998, Coleman and Melville 1994), where these relations are central to linkages between bedform propagation speed, sediment-transport rate and predictions of bed development. The development of dunes with varying flow (e.g. Coleman et al. 2005, Giri et al. 2008), not discussed herein, is an additional area requiring further research.

In terms of flow dynamics, the conjectured two-stage process of dune generation requires further verification of the details of both the identified eddy-generated bed disturbances preceding generation, and also disturbance-induced bed-stress profiles at initiation and associated sediment transport. The effects of bedform shape, including three-dimensionality (e.g. Best 2005a), bed mobility and sediment motion on the above-described flow structure for developing dunes, including $C_D = f(z)$, also requires further research. In this regard, the challenges of appropriate analysis of large spatial fields over developing dunes need to be addressed. It is expected that the equilibrium boundary layer nature identified herein for developing dunes will still be evident for these more complex systems, although flux-component magnitudes may be altered due to the additional flow complexities.

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REFERENCES

ASCE Task Committee on Flow and Transport over Dunes. 2002. Flow and transport over dunes. *J. Hyd. Engrg., ASCE*, 128 (8), 726-728.

Bennett, S. J. and Best, J. L. 1995. Mean flow and turbulence structure over fixed two-dimensional dunes: implications for sediment transport and bedform stability. *Sedimentology*, 42, 491-513.

Best, J. 2005a. The fluid dynamics of river dunes: A review and some future research directions. *J. Geophys. Res.*, 110, F04S02, doi:10.1029/2004JF000218.

Best, J. L. 2005b. Kinematics, topology and significance of dune-related macroturbulence: Some observations from the laboratory and field. In M. D. Blum, S. B. Marriott, and S. F. Leclair (eds.), *Fluvial Sedimentology VII, Spec. Publs. Int. Ass. Sediment.*, 35, 41– 60.

Cellino, M. and Graf, W. H. 2000. Experiments on suspension flow in open channels with bed forms. *J. Hyd. Res., IAHR*, 38 (4), 289-298.

Clunie, T. M., Nikora, V. I., Coleman, S. E., Friedrich, H., and Melville, B. W. 2007. Flow measurement using flying ADV probes. *J. Hydr. Engrg., ASCE*, 133, 12, 1345-1355.

Coleman, S. E. 1991. The mechanics of alluvial stream bed forms. PhD thesis, Auckland, The University of Auckland, 742 pp.

Coleman, S. E., and Eling, B. 2000. Sand wavelets in laminar open-channel flows. *J. Hyd. Res., IAHR*, 38(5), 331-338.

Coleman, S. E., Fedele, J. J., and García, M. H. 2003. Closed-conduit bedform initiation and development. *J. Hyd. Engrg., ASCE*, 129(12), 956-965.

Coleman, S.E., and Fenton, J. D. 2000. Potential-flow instability theory and alluvial stream bed forms. *J. Fluid Mech.*, 418, 101-117.

Coleman, S. E., and Melville, B. W. 1994. Bed-form development. *J. Hyd. Engrg., ASCE*, 120(4), 544-560.

Coleman, S. E., and Melville, B. W. 1996. Initiation of bed forms on a flat sand bed. *J. Hyd. Engrg., ASCE*, 122 (6), 301-310.

Coleman, S. E., and Nikora, V. I. 2008a. A unifying framework for particle entrainment. *Water Resources Research*, (in press).

Coleman, S. E., and Nikora, V. I. 2008b. Bed and flow dynamics leading to sediment-wave initiation. *Water Resources Research*, (in press).

Coleman, S. E., Nikora, V. I., McLean, S. R., Clunie, T. M., and Melville, B. W. 2007b. Subelement form-drag parameterization in rough-bed flows. *J. Hyd. Engrg., ASCE*, 133(2), 121-129.

Coleman, S. E., Nikora, V. I., McLean, S. R., Clunie, T. M., Schlicke, T., and Melville, B. W. 2006. Equilibrium hydrodynamics concept for developing dunes. *Physics of Fluids*, 18 (10), 105104-1-12.

Coleman, S. E., Nikora, V. I., McLean, S. R., and Schlicke, E. 2007a. Spatially averaged turbulent flow over square ribs. *J. Engrg. Mech., ASCE*, 133(2), 194-204.

Coleman, S. E., Nikora, V. I., Melville, B. W., Goring, D. G., Clunie, T. M., and Friedrich, H. 2008a. SWAT.nz: New-Zealand-based "Sand waves and turbulence" experimental programme. *Acta Geophysica*, (in press).

Coleman, S. E., Nikora, V. I., and Schlicke, T. 2008b. Spatially-averaged oscillatory flow over a rough bed. *Acta Geophysica*, (in press).

Coleman, S. E., Zhang, M. H., and Clunie, T. M. 2005. Sediment-wave development in subcritical water flow. *J. Hyd. Engrg., ASCE*, 131(2), 106-111.

Colombini, M. 2004. Revisiting the linear theory of sand dune formation. *J. Fluid Mech.*, 502, 1–16.

Ditchfield, R., and Best, J. 1992. Discussion of "Development of bed features," by A. Raudkivi and H.-H. Witte. *J. Hyd. Engrg., ASCE*, 118 (4), 647–650.

Engelund, F. A. 1970. Instability of erodible beds. *J .Fluid Mech.*, 42, 225-244.

Finnigan, J. J. 2000. Turbulence in plant canopies. *Annu. Rev. Fluid. Mech.*, 32, 519-571.

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

Fredsøe, J. 1986. Shape and dimensions of dunes in open channel flow. In F. El-baz and M.H.A Hassan (eds.), *Physics of desertification*, Martinus Nijhoff Publishers, Dordrecht, 385-397.

Giménez-Curto, L. A., and Corniero Lera, M. A. 1996. Oscillating turbulent flow over very rough surfaces. *J. Geophys. Res.*, 101(C9), 20,745-20,758.

Giri, S., Yamaguchi, S., Shimizu, Y., and Nelson, J. 2008. Simulating temporal response of bedform characteristics to varying flows. In C. M. Dohmen-Janssen and S. J. M. H. Hulscher (eds.), *River, Coastal and Estuarine Morphodynamics: RCEM 2007, Proc., 5th IAHR Symposium on River, Coastal and Estuarine Morphodynamics, Enschede, Netherlands, 17-21 September 2007*, Taylor & Francis Group, London, 939-947.

Gradowczyk, M. H. 1970. Wave propagation and boundary instability in erodible-bed channels. *J. Fluid Mech.*, 33, 93–112.

Grinvald, D. I., and Nikora, V. I. 1988. *River turbulence*. Hydrometeoizdat, Leningrad, Russia (in Russian).

Hino, M. 1968. Equilibrium-range spectra of sand waves formed by flowing water. *J. Fluid Mech.*, 34, 565-573.

Hyun, B. S., Balachandar, R., Yu, K., and Patel, V. C. 2003. Assessment of PIV to measure mean velocity and turbulence in open-channel flow. *Experiments in Fluids*, 35 (3) 262–267.

Jackson, R.G. 1976. Sedimentological and fluid-dynamic implications of the turbulent bursting phenomenon in geophysical flows. *J. Fluid Mech.*, 77, 531-560.

Jain, S. C., and Kennedy, J. F. 1974. The spectral evolution of sedimentary bed forms. *J. Fluid Mech.*, 63, 301-314.

Kadota, A. and Nezu, I. 1999. Three-dimensional structure of space-time correlation on coherent vortices generated behind dune crest. *J. Hyd. Res., IAHR*, 37 (1), 59-80.

Kennedy, J. F. 1969. The formation of sediment ripples, dunes and antidunes. *Ann. Rev. Fluid Mech.*, 1, 147-168.

Kleinhans, M. G. 2004. Sorting in grain flows at the lee side of dunes. *Earth Sci. Rev.*, 65, 75–102.

Kondrat'ev, N. E., Lyapin, A. N., Popov, I. V., Pin'kovskii, S. I., Fedorov, N. N., and Yakunin, I. I. 1959. *Channel processes*. Leningrad: Gidrometeoizdat.

Langbein, W. B., and Leopold L. B. 1968. River channel bars and dunes – theory of kinematic waves. U.S. Department of the Interior Geological Survey Professional Paper 422-L, U.S. Government Printing Office, Washington, USA, 20pp.

Liu, H.-K. 1957. Mechanics of sediment-ripple formation. *J. Hyd. Div., ASCE*, 83, 1-23.

López, F., and García, M. H. 2001. Mean flow and turbulence structure of open-channel flow through nonemergent vegetation. *J. Hyd. Engrg., ASCE*, 127(5), 392-402.

Lyn, D. A. 1993. Turbulence measurements in open-channels flows over artificial bedforms. *J. Hyd. Engrg., ASCE*, 119 (3), 306-326.

Maddux, T. B., McLean S. R., and Nelson, J. M. 2003b. Turbulent flow over three-dimensional dunes: 2. fluid and bed stresses. *J. Geophys. Res.*, 108 (F1), doi:10.1029/2003/JF000018.

Maddux, T. B., Nelson, J. M., and McLean, S. R. 2003a. Turbulent flow over three-dimensional dunes: 1. Free surface and flow response. *J. Geophys. Res.*, 108 (F1), doi:10.1029/2003/JF000017.

McLean, S. R. 1990. The stability of ripples and dunes. *Earth-Sci. Rev.*, 29, 131-144.

McLean, S. R., Nelson, J. M., and Gary, L. 2008a. Suspended sediment in the presence of dunes. In C. M. Dohmen-Janssen and S. J. M. H. Hulscher (eds.), *River, Coastal and Estuarine Morphodynamics: RCEM 2007, Proc., 5th IAHR Symposium on River, Coastal and Estuarine Morphodynamics, Enschede, Netherlands, 17-21 September 2007,* Taylor & Francis Group, London, 611-618.

McLean, S. R., Nelson, J. M., and Wolfe, S. R. 1994. Turbulence structure over two-dimensional bed forms: implications for sediment transport. *J. Geophys. Res.*, 99 (C6), 12729-12747.

McLean, S. R., and Nikora, V. I. 2006. Characteristics of turbulent unidirectional flow over rough beds: Double-averaging perspective with particular focus on sand dunes and gravel beds. *Water Resources Research*, 42, W10409, doi:10.1029/2005WR004708.

McLean, S. R., Nikora, V. I., and Coleman, S. E. 2008b. Double-averaged velocity profiles over fixed dune shapes. *Acta Geophysica*, (in press).

McLean, S. R., and Smith, J. D. 1986. A model for flow over two-dimensional bed forms. *J. Hyd. Engrg., ASCE*, 112, 300-317.

McLean, S. R., Wolfe, S. R. and Nelson, J. M. 1999. Spatially averaged flow over a wavy boundary revisited. *J. Geophys. Res.*, 104 (C7), 15743-15753.

Nakagawa, H., and Tsujimoto, T. 1984. Spectral analysis of sand bed instability. *J. Hyd. Engrg., ASCE*, 110(4), 467-483.

Nelson, J. M., McLean, S. R., and Wolfe, S. R. 1993. Mean flow and turbulence fields over two-dimensional bed forms. *Water Resources Research*, 29 (12), 3935-3953.

Nelson, J. M., Shreve, R. L., McLean S. R., and Drake, T. G. 1995. Role of near-bed turbulence structure in bed load transport and bed form mechanics. *Water Resources Research*, 31 (8), 2071-2086.

Nikora, V. I., Goring, D. G., McEwan, I., and Griffiths, G. 2001. Spatially-averaged open-channel flow over a rough bed. *J. Hyd. Engrg., ASCE*, 127(2), 123-133.

Nikora, V. I., and Hicks, D. M. 1997. Scaling relationships for sand wave development in unidirectional flow. *J. Hyd. Engrg., ASCE*, 123(12), 1152-1156.

Nikora, V., Koll, K., McEwan, I., McLean, S., and Dittrich, A. 2004. Velocity distribution in the roughness layer of rough-bed flows. *J. Hyd. Engrg., ASCE*, 130(10), 1036-1042.

Nikora, V. I., McEwan, I. K., McLean, S. R., Coleman, S. E., Pokrajac, D., and Walters, R. 2007a. Double-averaging concept for rough-bed open-channel and overland flows: Theoretical background. *J. Hyd. Engrg., ASCE*, 133(8), 873-883.

Nikora, V., McLean, S., Coleman, S., Pocrajac, D., McEwan, I., Campbell, L., Aberle, J., Clunie, D., Koll, K. 2007b. Double-averaging concept for rough-bed open-channel and overland flows: applications. *J. Hyd. Engrg., ASCE*, 133(8), 884-895.

Nikora, V. I., Sukhodolov, A. N., Rowinski, P. M. 1997. Statistical sand wave dynamics in one-directional water flows. *J. Fluid Mech.*, 351, 17-39.

Niño, Y., Atala, A., Barahona, M., and Aracena, D. 2002. Discrete particle model for analysing bedform development. *J. Hyd. Engrg., ASCE*, 128(4), 381-389.

Raudkivi, A. J. 1966. Bed forms in alluvial channels. J. Fluid Mech., 26(3), 507-514.

Raudkivi, A. J. 1997. Ripples on stream bed. *J. Hyd. Engrg., ASCE*, 123(1), 58–64.

Raudkivi, A. J. 1998. *Loose boundary hydraulics*. 4th Ed., Pergamon Press, Inc., New York, New York, U.S.A., 496pp.

Raudkivi, A., and Witte, H.-H. 1990. Development of bed features. *J. Hyd. Engrg., ASCE*, 116(9), 1063-1079.

Raupach, M. R., Antonia, R. A., and Rajagopalan, S. 1991. Rough-wall turbulent boundary layers. *Appl. Mech. Rev., ASME*, 44 (1), 1-25.

Richards, K. J. 1980. The formation of ripples and dunes on an erodible bed. *J. Fluid Mech.*, 99(3), 597-618.

Sirovich, L., and Karlsson, S. 1997. Turbulent drag reduction by passive mechanism. *Nature*, 388, 753-755.

Smith, J.D. 1970. Stability of a sand bed subjected to a shear flow of low Froude number. *J. Geophys. Res.*, 75(30), 5928-5940.

Smith, J. D., and McLean, S. R. 1977. Spatially averaged flow over a wavy surface. *J. Geophys. Res.*, 83(12), 1735-1746.

Stoesser, T., Braun, C., García-Villalba, M., and Rodi, W. 2008. Turbulence structures in flow over two-dimensional dunes. *J. Hyd. Engrg., ASCE,* 134 (1), 42-55.

van Mierlo, M. C. L. M. and de Ruiter, J. C. C. 1988. Turbulence measurements above artificial dunes. Report. Q789, Delft Hydraulics, the Netherlands, 42pp.

Velikanov, M. A. 1955. *Dynamics of alluvial streams. Vol. II. Sediment and bed flow*. State Publishing House for Theoretical and Technical Literature, Moscow.

Venditti, J. G. 2007. Turbulent flow and drag over fixed two- and three-dimensional dunes. *J. Geophys. Res.*, 112, F04008, doi:10.1029/2006JF000650.

Venditti J. G., and Bennett, S. J. 2000. Spectral analysis of turbulent flow and suspended sediment transport over fixed dunes. *J. Geophys. Res.*, 105 (C9), 22035-22047.

Venditti, J. G., Church, M. A., and Bennett, S. J. 2005. Bed form initiation from a flat sand bed. *J. Geophys. Res.*, 110, F01009, doi:10.1029/2004JF000149.

Venditti, J. G., Church, M., and Bennett, S. J. 2006. On interfacial instability as a cause of transverse subcritical bed forms. *Water Resources Research*, 42, W07423, doi:10.1029/2005WR004346.

Wilson, N. R., and Shaw, R. H. 1977. A higher order closure model for canopy flow. *J. Appl. Meteorology*, 16, 1197-1205.

Yalin, M. S. 1992. *River mechanics*. Pergamon Press, Inc., New York, N.Y., U.S.A.

Yue, W., Lin, C.-L., and Patel, V. C. 2005. Coherent structures in open-channel flows over a fixed dune. *J. Fluids. Engrg., ASME*, 127 (5), 858-864.

Yue, W., Lin, C.-L., and Patel, V. C. 2006. Large-eddy simulation of turbulent flow over a fixed two-dimensional dune. *J. Hyd. Engrg., ASCE*, 132 (7), 643-651.

Zhou, D., and Mendoza, C. 2005. Growth model for sand wavelets. *J. Hyd. Engrg., ASCE*, 131(10), 866-876.