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Aeolian and fluvial grain transport

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The processes of aeolian and fluvial grain transport have several superficial similarities, but differences of detail are also important. In both systems, transport rate variations produce bed forms, such as dunes, and modify bed composition. Transport rate depends on entrainment and deposition processes. Entrainment into the flow can be more compactly described in the aeolian case, on the basis of the statistics of observed collision, inter-saltation collision being the primary agent of aeolian entrainment. Consequently, this transport process can be modelled with reasonable success.

Grain entrainment by water is more difficult to observe, because the readily observable mobile grains are not significant intermediaries in the process. The dependencies of entrainment are therefore less well understood, and grain transport has been modelled with more limited success. However, modelling exercises help to identify clearly the points at which understanding of grain behaviour is deficient and are useful for this purpose. Fluvial grain entrainment and deposition are heavily influenced by the bed composition and arrangement as well as by the flow, so programmes of observation and modelling should pay particular attention to the bed state.

Keywords: sediment transport; entrainment and deposition; saltation layer modelling

1. Introduction

The results of aeolian and fluvial transport of granular solids are of general interest because they are evident in many, often attractive, landscape features (figure 1). They are of professional interest to geographers, geologists, agriculturalists, ecologists, meteorologists and engineers. The results include changes in topography and the composition and structure of underlying strata, in air quality, in the movement and quality of surface and groundwater, and in soil fertility.

Aeolian and fluvial transport have a number of common features in terms of both outcome and process. Both produce ripples and dunes under certain circumstances, and both can involve bed load and suspended load processes. However, there are also important distinctions between the two transport systems (Bagnold 1941) arising from differences between atmospheric and river flow structures, and particularly from the great difference between the ratios of the densities of grain and transporting medium. For quartz grains in air, this ratio exceeds 2000:1, but in water it is *ca.* 2.6:1. In consequence, water transports a much greater range of grain sizes than air, while the direct collision of grains is much more important in air–grain transport than in fluvial systems.

Investigators have traditionally taken one of two distinct approaches to the two topics, either categorizing morphological features first and seeking explanations for

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Figure 1. The River Dee near Braemar; fluvial features inscribed in a glaciated valley.

them in terms of the transport processes, or examining processes by means of experiments and physical argument with a view to modelling the morphology. There is a healthy modern trend towards convergence of the two approaches and improvement of communication between field and laboratory scientists. Evidence of such a trend can be found in publications on both aeolian (Barndorff-Nielsen & Willetts 1991) and fluvial systems (Thorne *et al*. 1997), which also demonstrate ample scope for further cross-fertilization between the two schools of thought. Engineers, because of their responsibilities for intervention in natural systems, often operate in the uncomfortable hinterland between grain-scale studies and observation of natural bed forms. Their need is for methods of prediction that are reliable at the range of scales set by particular problems. These range from localized scour–deposition patterns where a fixed structure is to intrude into a river flow or field of aeolian sand transport, to catchment-wide considerations influencing reservoir silting or river flood management. Methods of prediction reliable over this range of scales require a sound understanding both of grain–flow mechanics and of related topographical forms. Such tools are not yet available. There is a continuing search for an adequate analytical framework, against a background of acute difficulty in observing the transport processes.

This paper will review the aeolian and fluvial systems in outline, and comment on the time- and length-scales involved. It will explore the features of the transport processes that contribute to grain size sorting, which is of particular practical importance. To illustrate present knowledge of the two systems, and its gaps, the paper will go on to describe a comparatively successful aeolian model and to outline progress and difficulties in developing a corresponding model of fluvial transport. Reviews of the much broader fields from which this limited treatment is drawn are provided by Greeley & Iverson (1985) and Thorne *et al*. (1997).

Figure 2. A dust cloud entering Melbourne. The material comes from the Mallee region 500 km north of Melbourne, but is approaching the city from the south.

2. Review of the transport processes

In both aeolian and fluvial grain transport systems, initial dislodgement of the 'first generation' mobile grains is effected by flow forces overcoming the stabilizing influences of grain weight and any interlock with neighbouring bed grains. Dislodged grains may roll and saltate (hop) before depositing again onto the bed quite soon, or may become suspended and undertake prolonged excursions before redeposition. Suspended grains have their paths extended and prolonged by turbulent mixing of the fluid, sometimes travelling hundreds of kilometres in rivers and many thousands of kilometres in the atmosphere. Figure 2 shows a cloud of dust entering Melbourne from the south, having originated in the Mallee 500 km to the north, travelled out over the Southern Ocean and then returned, apparently from the sea.

Rolling and saltating grains comprise the 'bedload'. A single excursion may begin with rolling and develop into a sequence of saltations ending in deposition or, occasionally, entry into suspension. In the aeolian system, saltation assumes particular importance because the inter-saltation collisions have sufficient momentum to dislodge stationary grains and, indeed, beyond the first generation of dislodgements, soon become the primary agent for entraining grains into both bedload transport and suspension in air. A stable population of saltating grains is maintained in steady flow when the rates of deposition and entrainment are balanced; Anderson & Haff (1988) have referred to a matched 'birth rate and death rate' of saltations.

In water, because the momentum of a grain at the end of a saltation is only two and a half times that of the water it displaces, the role of collision in entrainment is much less important. Displacements are assumed to continue to be effected by

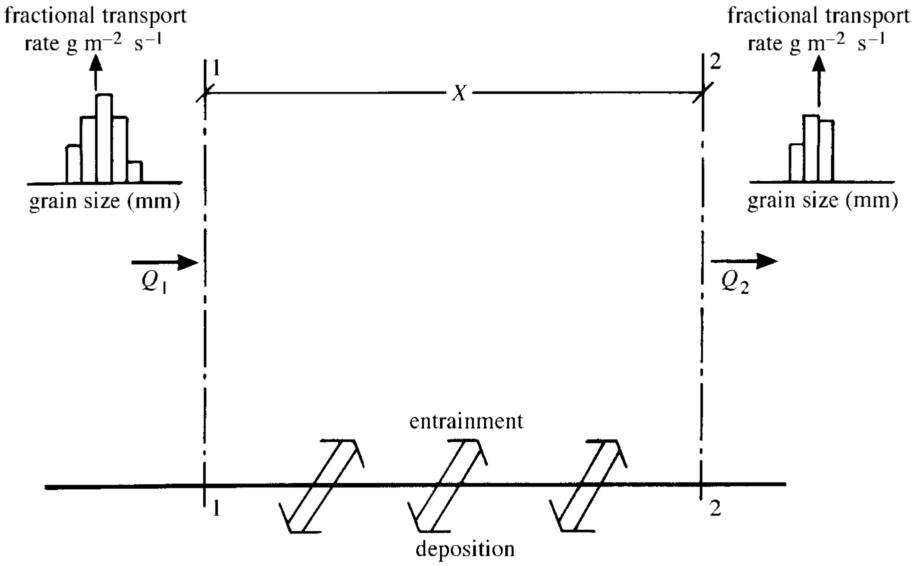

Figure 3. Sediment gains and losses of a control volume, length X. The fractional transport rates at cross-sections 1 and 2 are inset.

peak values of the fluid forces. There is some evidence that they occur preferentially during turbulent sweeps (Gallagher & McEwan 1996).

Broadly, in both systems, suspended load comprises fine (or low-density) grains travelling long distances at high speed (approximately that of the flow) while bedload consists of coarser grains travelling in shorter excursions at lower speed. There are contributions to grain sorting from selectivity in the dislodgement process, where this occurs, and from the differences in typical excursion between the dislodged size fractions. Deposition of moving grains at the end of their excursions is influenced by the flow structure in the deposition zone and by the texture of the bed there (and hence the availability of stable landing sites). Both of these factors affect different sized grains differently, so deposition tends to sort by size fraction.

Figure 3 illustrates the exchange between the bed and the transported load, without distinguishing between bedload and suspended load, in a control volume of unit width, of great height, and of length X. If the rates of deposition and entrainment are equal for each size fraction in the transported load, then the rate at which sediment leaves the control volume and the composition of the sediment load at cross-section 2 must both be identical to conditions at the entry cross-section, 1. However, if, for example, the deposition rate exceeds the entrainment rate for one or more size fractions, then the bed elevation and the compositions of both the transported load and the bed surface are all modified. The deposit composition can be obtained by subtracting the fractional transport rate histogram at cross-section 2 from that at cross-section 1. Conversely, if the entrainment rate exceeds the deposition rate, the bed elevation is reduced; the size composition at the bed surface also changes if the erosion process is selective, as it sometimes is.

Distance X in figure 3 may be chosen to be very small, in which case the erosion rate and the deposition rate may each be considered uniform over the base of the control volume. The bed elevation and composition may also be considered uniform.

Change with time of the elevation is related to the transport rates as

$$\sum_{k=1}^{n}(Q_{1k} - Q_{2k}) = \rho_s X \frac{\Delta y}{\Delta t}, \tag{2.1}$$

where Q_{1k} and Q_{2k} are transport rates of fraction k at cross-sections 1 and 2, y is bed elevation and ρ_s is the bulk density of material in the bed.

In limited circumstances and with very generous error bounds, in each of the two systems, it is possible to calculate local values of total transport rate (undifferentiated with regard to size fraction) from empirically derived formulae that use a flow variable such as boundary shear stress. The substitution of such values in equation (2.1) enables bed morphology to be modelled, using repeated solutions of the flow field as the flow boundary changes to estimate the distribution of boundary shear stress. The equation is easily adapted to three-dimensional coordinate systems when the nature of the flow field requires it.

Were there procedures available for calculating transport rate fraction by fraction from local values of one or more flow variables, then changes in bed composition could also be predicted. However, because the composition of the transported load depends on the availability of grains for entrainment as well as on the flow, it is futile to seek a formula for transport rate using flow parameters without reference to the bed condition. It seems rather that, with reference to figure 3, fractional transport rate changes must be calculated using entrainment and deposition process rates based on the bed composition and structure, and on the flow. We shall consider the entrainment and deposition processes further below.

If the streamwise dimension X of the control volume in figure 3 is made longer than a few millimetres, then the grain activity at the bed ceases to be uniform over X because of its variation over features such as ripples, dunes and irregularities in plan. When X is of order 10 cm, variations over ripple profiles are included; at order 10–100 m, so are variations in grain activity associated with dunes; at progressively higher values of X, river planform irregularities (e.g. meanders and changes in width) are included in the control volume. Equation (2.1) then loses its direct usefulness in modelling because $\Delta y/\Delta t$ and probably ρ_s vary with streamwise (and spanwise) position within the control volume. Nevertheless, large control volumes retain considerable value, in conjunction with satellite or airborne radar imagery in such tasks as estimating aggregated dust production or water-borne sediment yield from extensive source areas. In this case, however, the accumulation term on the right of the equation must be replaced by an expression that integrates the quantity over the base of the control volume.

Aeolian entrainment and deposition each differ sufficiently from the corresponding process in water that it is appropriate to consider them separately.

(*a*) *In air*

In air, the predominant entrainment mechanism is the collision with the bed of saltating grains, usually in the size range 0.15–0.35 mm. Grains approach the bed at a variety of incident angles, generally in the range 9–14°, at velocities up to, and occasionally exceeding, 10 times the shear velocity. (Many approach velocities are smaller than this, resulting from small, low saltations.) There is a high probability of rebound of incident grains and of dislodgement of bed grains in the vicinity of the impact. Of the dislodged grains, some adjust their position without losing contact with the bed and so contribute to bedload transport in a 'creep mode'. Others are ejected from the bed by the collision and may saltate or become suspended. In high winds the population of saltating grains near the bed is dense enough for airborne collisions to become common (Sorensen & McEwan 1996) and a collision-dispersed layer to form.

The average number of ejections, their launch velocities and the creep adjustments are functions of the bed composition and topography (Hunt & Nalpanis 1985; Willetts & Rice 1986; Rice *et al*. 1996). Grains greater than 1.50 mm are too massive to be dislodged by inter-saltation collisions. Those greater than 0.6 mm may creep or roll forward but do not join the saltating population, much less the suspended load. Wind blowing landward over a beach drives grains in the size range 0.15–0.35 mm into the dunes, spreads any finer material for some kilometres inland by suspension, and leaves coarser material on the beach. In consequence, coastal dunes are particularly well sorted. Material fine enough to be suspended is progressively lost from the beach–dune subsystem, as it is lost from arable land when wind erosion takes place. Thus, sorting at entrainment into the aeolian system is uncomplicated in principle, if not in detail, being based first on the inertia ratio between the colliding grain and those in the collision zone, and then on the susceptibility of detached grains to the influence of turbulence and hence diffusion upwards into suspension. There is a quite well-defined limit of size (or, more strictly, mass) for those grains that participate in aeolian transport. Simplified models of the saltation and suspension processes are each quite successful in replicating those features that can be measured with confidence, but there remains doubt about the way in which the suspension process is fed from the saltation layer, or directly from the bed. Figure 4 shows the disturbance of 0.05 mm grains from a homogeneous surface by impact of a grain of *ca.* 0.2 mm. While the path of the larger grain is sufficiently regular, as indicated by its stroboscopically illuminated positions, to suggest that turbulence has negligible effect on it, those of the smaller grains are more erratic. They are more susceptible to influence by turbulence and a proportion (small at the wind speed of this photograph) are likely to be entrained into suspension.

(*b*) *In rivers*

In rivers, the range of active sizes may be many orders of magnitude greater (from clay particle size to family car size) and the sorting processes more complex. Even setting aside the complexities of cross-section change and of planform geometry, the interaction of such a great range of mobile grain size fractions and the hydrological fluctuations with time create a hugely complicated system. The scope for reliable prediction is limited to a few well-researched areas of the extensive field of interest.

Consider, for example, the entrainment and redeposition of sand and gravel in a straight reach of a gravel-bed river, having a grain size range of *ca.* 0.6–60 mm. For a large proportion of the time, flow in the river is too low to disturb the bed, the superficial appearance of which is dominated by the largest grains in the bed material. In this condition, there is no significant sediment transport unless fine material enters the reach and passes through it in suspension, without interaction with the bed. When a discharge occurs that is large enough to disturb the bed, the entrainment and deposition occurring in our chosen reach depend on several factors, including the following.

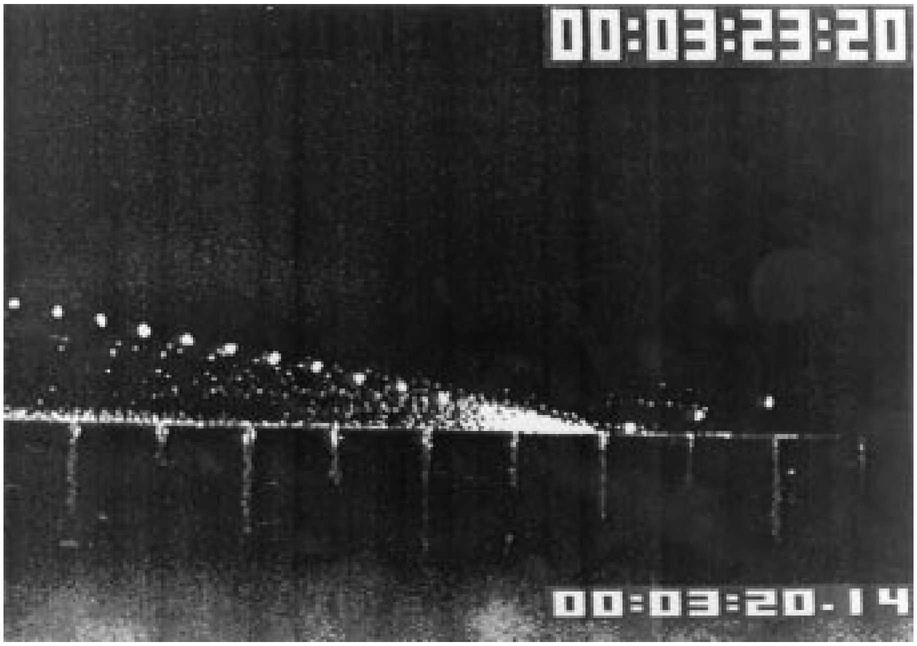

Figure 4. Collision of a saltating grain in the size range 0.2–0.25 mm with a bed of 0.05 mm grains.

1. The bedload entering the reach, its transport rate in relation to the transporting capacity of the reach, and its composition.
2. Whether the flow is high enough to dislodge grains of all the sizes present, or only some of the finer fractions.
3. The composition of the bed and the organization of grains in the surface layer.
4. The duration of the sediment-disturbing flow intensity and its rate of recession.

Laboratory studies have generally employed straight channels with uniform cross-section and bed slope, and have examined one of two particular cases of entering bedload: either matching the entering bedload to that discharging at the tail of the channel (by recirculation of sediment) or having no entering bedload. The two arrangements promote quite different interactions between the transported load and the bed. They can be regarded as particular conditions between which many natural river conditions lie (Parker & Wilcock 1993). There are a smaller number of data sets from experiments in which sediment was introduced to the flow near the upstream end of the channel, producing a sediment load surcharge and lying beyond the recirculation case, but still representative of conditions that sometimes occur naturally.

In sediment recirculation experiments (Wilcock & McArdell 1993), there is a range of flows for which grain entrainment is selective and the bedload composition is different from that of the bed. This has been termed a regime of partial mobility. The bed composition is slightly changed, and would be changed much more radically but for the constraint of recirculation, which amplifies the availability for deposition

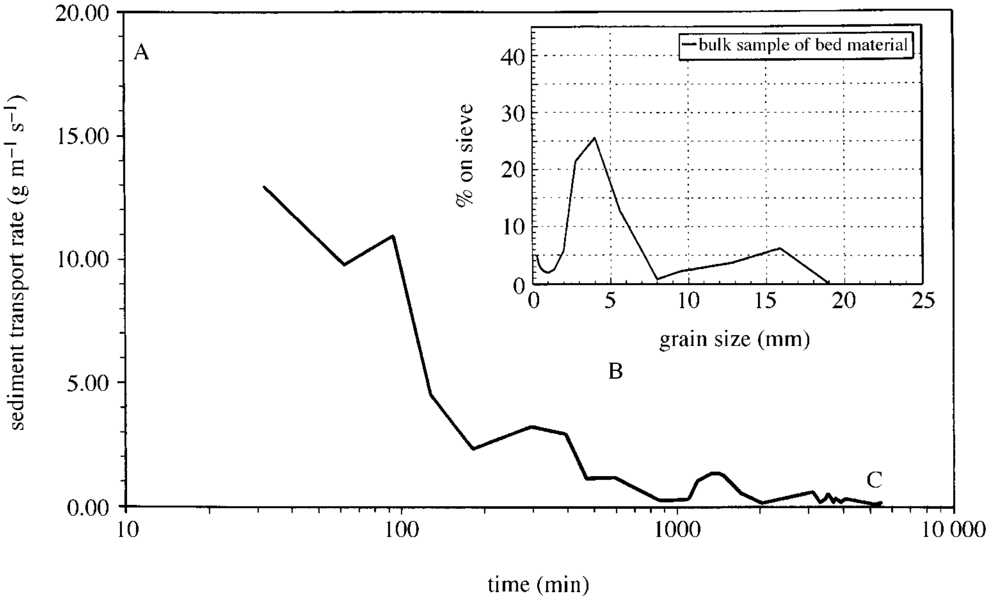

Figure 5. The change with time of transport rate of a sand/gravel sediment in constant flow conditions in a laboratory channel. No sediment enters the channel.

in the same reach of those fractions that have been preferentially entrained from it. At higher flows, a condition develops that has been called 'equal mobility'. Here, the bedload composition matches the surface composition of the bed, all size fractions being active and entrainment being unselective.

In experiments in which no sediment enters the channel and bed material is entrained, the bed elevation is lowered, as equation (2.1) makes clear. This bed degradation may be arrested by the exposure of a virtually unerodable surface (perhaps rock) when the flow is strong enough to mobilize all size fractions of the bed material or, when the largest fractions are not mobilized by the flow, by the formation of an 'armour layer' of large grains protecting the finer ones from entrainment. The transport rate decays with time as the armour layer forms, as illustrated in figure 5. Two stages in the process have been identified (Tait *et al*. 1997). In the first stage (A to B in figure 5), some fine grains are winnowed from the surface, and in the second (B to C in figure 5) the grains remaining at the surface are rearranged, increasing the surface roughness and providing more shelter for the fine grains remaining in the surface layer. However, determination of the composition and structure of the surface is extremely difficult and this two-stage view of the armouring process is likely to be revised as observational technique improves.

Figure 5 uses data from an experiment which started from a hand-placed and screeded bed and might be questioned on the basis that the artificial surface interacts with the flow in a way untypical of natural beds. Figure 6 shows data from an experiment in which sediment was fed to the channel at the rate and for the duration indicated *ca.* 15 m upstream of the section at which transport rate was measured. Two points are of particular interest in comparison with figure 5. In the early stages of the fed experiment, the transport rate appears to have been suppressed by the surcharge of sediment produced by feeding, and after restoration of the transport rate and discontinuing of the feed, the transport rate declines with time much as it did over the artificial bed, although by this stage of the experiment the bed is clearly a construct of the earlier water-working. During the final stages of the experiment, the bed roughness was observed to increase as it had in the experiment of figure 5. Both of these experiments were conducted in the domain of partial mobility, with the same sediment mix (for which generally consistent results were obtained at different bed slopes and flows), so it is fair to compare them directly. The results have limited general significance until the behaviour of a number of differently graded bed sediments has been observed. At present, the implications from these and earlier experiments (e.g. Proffitt & Sutherland 1983; Wilcock & McArdell 1993; Bennett & Bridge 1995) might be summarized as follows.

1. Bed composition and texture (or roughness) generally change during sediment transport when the bed contains a range of sediment sizes.

2. Sediment entrainment and deposition, and their selectivity with regard to size, are influenced by the surface composition and roughness of the bed as well as by the flow intensity.

3. Therefore, the transport rate, and the bedload composition, may be expected to change with time (figure 3).

4. Recession of a sediment-transporting flow may leave the bed in a state of arrest uncharacteristic of any single earlier flow but strongly influenced by the rate of recession.

5. Among the possibilities following fast recession of a flow with a heavy sediment load is successive deposition of size fractions, producing deposits sorted by size (more strictly settling velocity) both in the stream direction and vertically.

6. Many sequences of sediment activity and its arrest, as a river wanders back and forth over its flood plain, produce an extremely complicated ground structure which influences both later behaviour of the river and the engineering properties of the flood plain.

In summary, both aeolian and fluvial grain transport promote mixture re-sorting. The important selective subprocesses include entrainment and deposition at the bed, exchanges between the bedload and the suspended load, and changes of the flow regime in time and space. The system response at a particular time is strongly conditioned by system ‘memory’ of earlier events.

There are important differences between the aeolian and the fluvial systems and substantial gaps in our understanding of each of them. The gaps are much greater for the fluvial system despite a large research effort throughout this century. There are more than 50 rival formulae for predicting sediment transport rate in water and no adequate guidance as to the range of reliability of each. This is unsatisfactory from the point of view of those with practical design and management responsibilities, and arises from the failure of many investigators to identify the relevant variables, to prioritize their importance in different circumstances, and to measure their values reliably. Measurement methods have improved greatly in the past decade and there

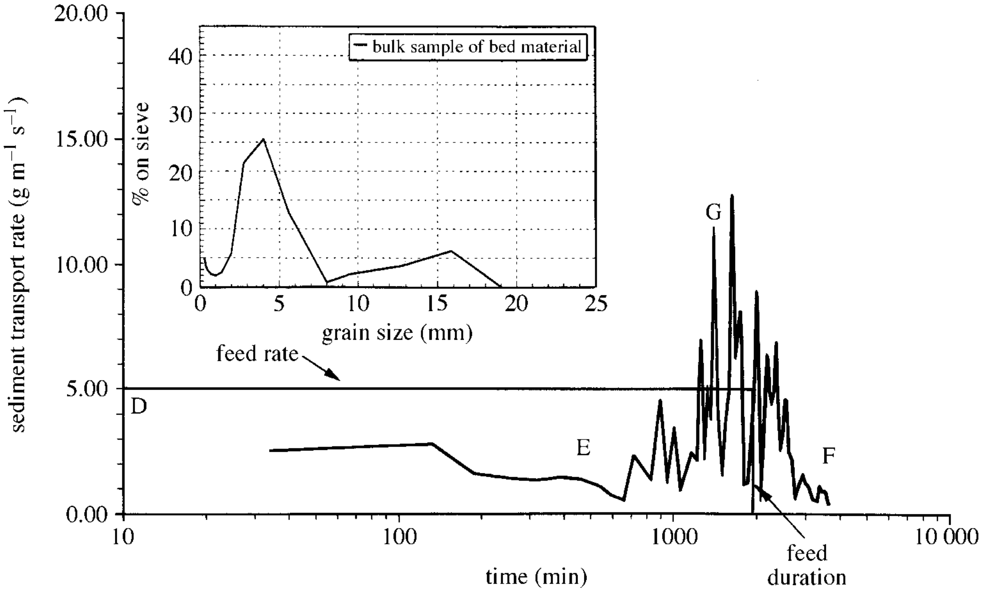

Figure 6. Transport rate change in the same channel and at the same flow condition as shown in figure 5. Sediment feed at the rate indicated is now surcharging the flow for the period indicated.

is an urgent need to take advantage of the opportunity thus created to clarify some of the obscure issues. Numerical models are useful aids in identifying the scope of gaps in understanding and hence planning theoretical and observational campaigns of investigation.

The following sections will outline modelling essays concerning aeolian and fluvial transport, respectively, to illustrate the two processes and some of the remaining obscurities surrounding them.

3. Aeolian saltation cloud models

There are several published models of the aeolian saltation cloud and its interactions with the bed and with the wind (e.g. Ungar & Haff 1987; Anderson & Haff 1988, 1991; Werner 1990; McEwan & Willetts 1991, 1993; Sorensen 1991; Spies 1995). They have many common features. The following account will focus on the models of McEwan & Willetts (1991, 1993) and Spies (1995) for convenience of illustration and without implying them to be better than others of the type.

The model architecture is illustrated in figure 7. A neutral atmospheric boundary layer, hereafter called the wind, suddenly encounters a boundary composed of sand grains. A few grains, dislodged by aerodynamic forces, enter saltation. At the end of each saltation, each grain collides with the bed, probably rebounding and possibly dislodging other grains. The outcome of collision is embodied in the model by means of a 'splash function' derived statistically from observation of many collisions (e.g. Willetts & Rice 1986). The path of each grain leaving the bed is computed from equations of motion incorporating drag and mass terms based on the assumption that the grain is spherical and, in the drag term, a time-averaged wind profile (neglecting turbulent fluctuations). The profile is divided into discrete increments of height above the bed and the grain exchanges momentum with each layer through

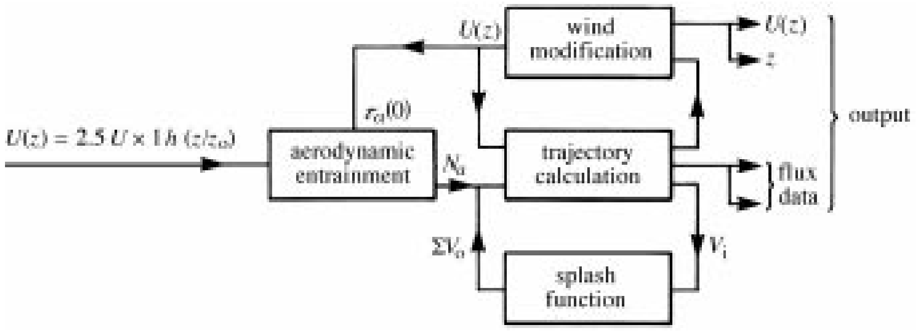

Figure 7. A schematic diagram of the subprocesses incorporated in the saltation model and their linkages.

which it passes. As a result of the passage of many saltating grains, each near-bed layer is retarded. Later saltations therefore encounter a modified wind profile; consequently, they become progressively less energetic and their splash functions less productive. The development of saltation is stabilized by these coupled feedback loops, as indicated in figure 7.

The model of McEwan & Willetts (1993) is constructed with a periodic boundary in the flow direction and conditions are considered uniform in the transverse direction. A free-stream driving flow is provided at an arbitrarily chosen height above the bed (at the limit of the computation domain). A boundary condition is imposed that the fluid shear stress at this height tracks the shear stress applied to the bed (by fluid shear and grain impact). The results show a saltation layer development in time, synchronous for all streamwise positions, because of the periodic boundary.

The empiricism in models of this kind is restricted to definition of the splash function and the assignment of drag coefficient values. Therefore, successful replication of observed process features is evidence of a degree of soundness in the physical basis of the model. Figure 8 shows progressive modification of the wind profile as the population of saltating grains grows, for an initial shear velocity of $0.32\ \mathrm{m\,s^{-1}}$. Figure 9 illustrates the growth of sediment transport rate (or mass flux) in simulations at four different values of shear velocity. For three of these values, equilibrium transport rate is reached in two stages; first a build up of the saltating population in *ca.* 1 s, and then adjustment of the wind profile to the presence of saltation in rather more than 5 s. The variation of equilibrium mass flux with shear velocity is plotted in figure 10 and reproduces the cubic relationship deduced by Bagnold (1941).

It is common observation, on any windswept beach, for example, that grain activity is neither uniform nor steady. In particular, it is strongly influenced at a given location by wind gusts in a manner that the model of McEwan & Willetts cannot reflect. Spies (1995) restructured the model, dispensing with the periodic boundary and imposing wind speed as a function of time at the upper boundary of computation. This model shows development of the saltation cloud in streamwise space as well as time and enables the response to gusts to be explored by the application of a gusty driving wind. Figure 11 indicates the progress of the saltation cloud associated with a localized ($x = 0$–$10\ \mathrm{m}$) and short duration ($t = 0$–$0.1\ \mathrm{s}$) release of saltators with aerodynamic entrainment restrained (to isolate the impactive contribution to the population). In a small number of runs, the presence of gusts was found to increase the mean transport rate for a given mean wind speed. Further system-

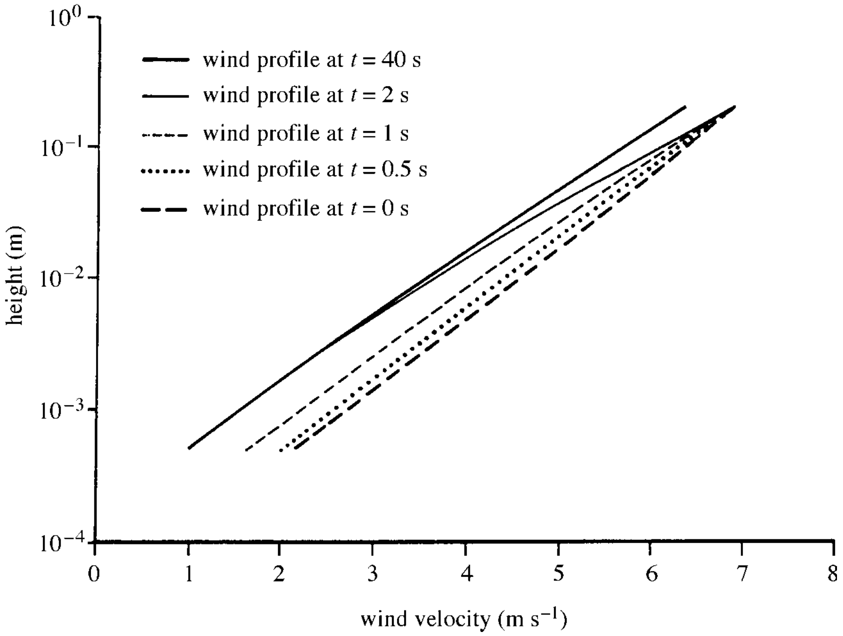

Figure 8. Progressive modification of the wind profile, driven by the momentum exchanges with saltating grains. The initial 'clean air' profile is assumed to be logarithmic.

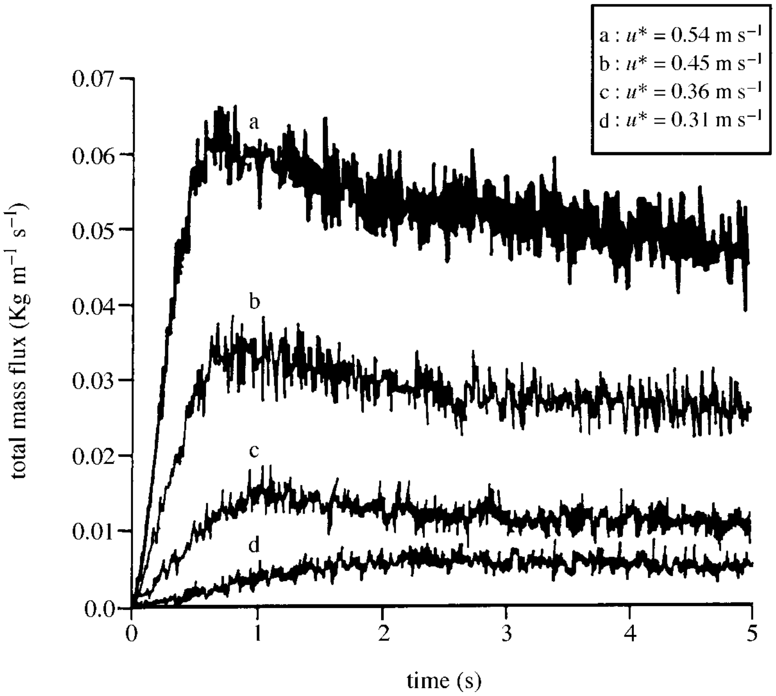

Figure 9. Modelled development with time of the aeolian sediment transport rate at four different values of shear velocity, as indicated.

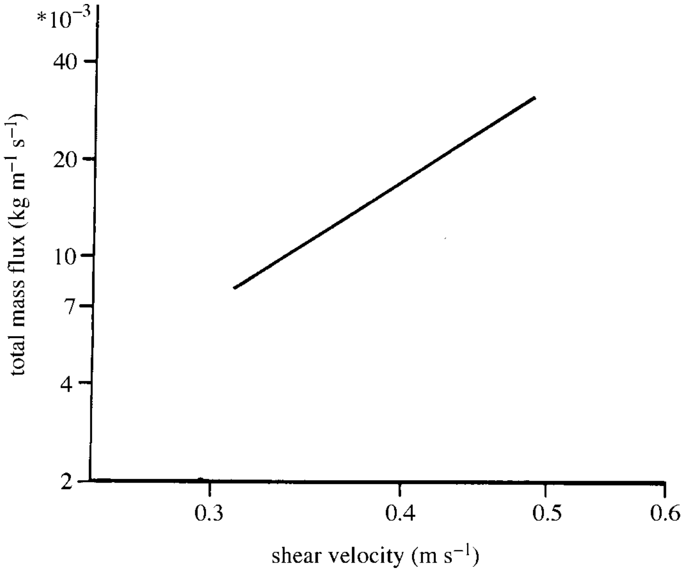

Figure 10. Variation of the equilibrium mass transport rate of sediment with shear velocity.

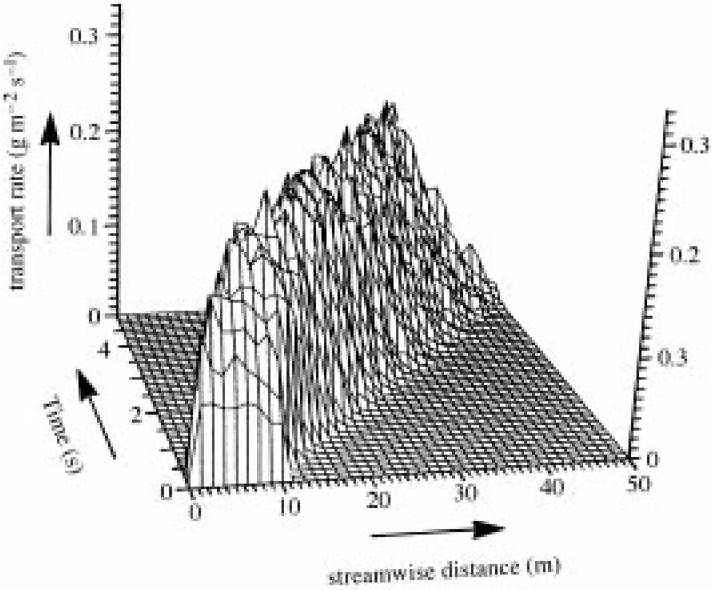

Figure 11. A simulated localized gust mobilizes sediment between 0 and 10 m for an interval of 0.1 s. The saltation pattern induced propagates downwind as shown.

atic investigation is required of the effects of gust intensity, duration and frequency which, by implication, have been shown to be important in predicting transport rate. Another implication of Spies's work is that wind-tunnel experiments systematically under-predict transport rate for field conditions at the corresponding shear velocity.

It should be noted that empirical definition of splash functions for incorporation in models restricts the versatility of such models. Structural features of field deposits, such as packing and stratification, are unlikely to have been replicated in the experiments on which splash functions are based. Therefore, the use of such functions limits model fidelity to field conditions by neglecting the system memory of the history of the deposit.

4. An essay in fluvial transport rate modelling

The key to the success of these aeolian models is the dominance of ballistic dislodgement and the reasonably readily defined splash function (with the qualification noted in the last paragraph). This enables the exchanges with the bed, seen to be so important in figure 3, to be incorporated very simply. A corresponding short cut is not available to the fluvial grain transport modeller. In this system, grains are generally dislodged by fluid-generated forces, at the times and places at which peak turbulent velocities encounter grains of low stability. Their excursions are strongly influenced by secondary currents and turbulent fluctuations, and their eventual deposition by the statistics of encounters with 'hospitable' bed locations. Such a location has to provide at least a contact geometry stable in relation to an approaching grain's size, and probably a degree of shelter from the prevailing flow as well. These complications make fluvial modelling much more difficult than aeolian modelling.

An exploration of its problems has been undertaken by Jefcoate (1995) by adaptation and extension of the aeolian model of McEwan & Willetts (1993). His simulation begins with the construction of a bed of spheres (in one example of three sizes) by dropping grains one by one from random plan coordinates into the 'virtual channel' used in the numerical experiments. This produces a bed (figure 12) that is slightly organized because of the tendency of stable locations for large grains to be associated with pre-existent groupings of large grains. The surface of this bed is then exposed to the action of the computational flow.

Each grain exposed to the flow is subject to fluid forces that may dislodge it, depending on their magnitude and on the geometry of its contacts with other grains and the shelter provided by its position. The stability of each surface grain is explored at each model time-step and the excursion and deposition are calculated of each mobilized grain. A running account is kept of the grain rearrangements so produced. In tracking the excursion, each encounter with the bed is regarded as an opportunity for deposition and the stability of the contact position is examined. So its progress from one trial landing site to another is calculated until it finds a stable one and comes to rest. The current coordinates of all grains are retained, so a plot of the bed can be obtained at any time.

In simulations of experiments reported by Wilcock & Southard (1989), the model produced reasonable grain excursion velocities, transport rates and coarsening of the surface composition (providing that the driving flow fluctuated to simulate turbulence). However, the changes in surface composition were produced much faster than they have been observed to occur in reality. Jefcoate suggests a number of contributory reasons for the collapsed time-scale.

There are several weaknesses evident in the model that are unavoidable at present, but that point to future research needs. The most acute of these concern exploration of the near-bed wind climate, including the effects of shelter provided by the surface topography upstream of the grain under examination. Nevertheless, the model provides useful clues about the importance of surface texture to transport rate, the

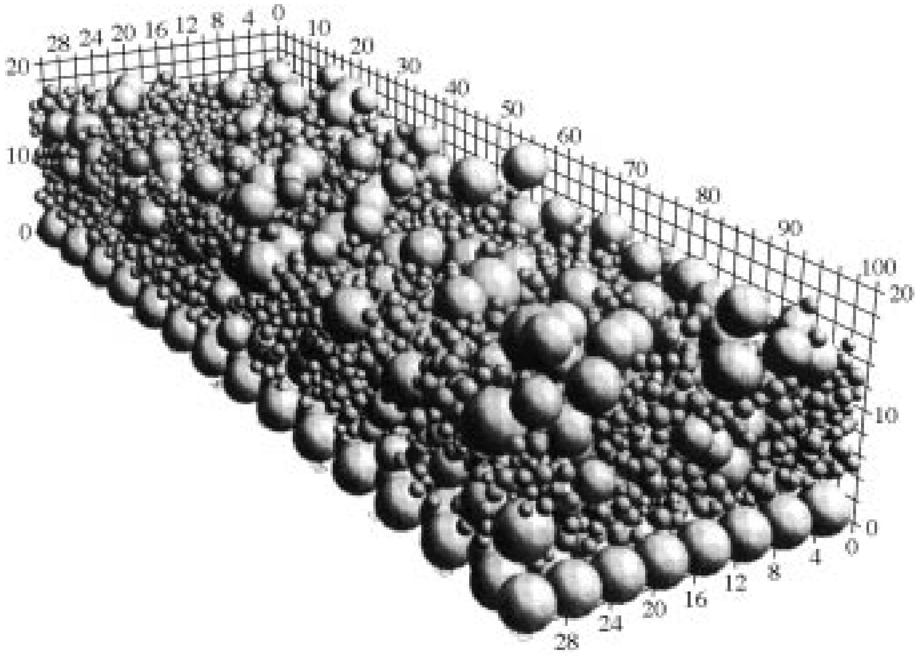

Figure 12. The model bed, composed of spheres of three sizes (1.5, 2.5 and 5 mm), obtained by dropping individual grains at random plan positions into the computational space that will later become the virtual flow channel. Some clustering of grain sizes is evident despite the absence of any flow. (Dimensions indicated in millimetres.)

variability of stability of exposed grains, and the sensitivity of grain behaviour to turbulence structure. While such grain-by-grain treatments are unlikely ever to provide useful tools of field-scale prediction, they may be valuable in validating the interrelationships incorporated in models that deal stochastically with bulk behaviour of grains in transport. For example, they might be used to evaluate the 'hiding functions' that are commonly used to relate transport rates of the several fractions of poorly sorted sediments to those of corresponding uniform sediments.

5. Concluding remarks

It has been postulated that better knowledge of the bed–fluid interface and the entrainment and deposition processes is the key to further progress in sediment transport mechanics. This is particularly marked now that powerful flow solvers are generally available to determine flow in the wider problem domain of the river cross-section or the lower atmosphere. When a compact description of events at this interface is available, as in the aeolian transport case, remarkably good model results can be achieved (albeit for rather straightforward circumstances). This suggests that clarification of the more complex interactions at the bed–water interface is an objective worthy of significant investment.

These interactions are generally influenced by, and influence, the grain size distribution and grain arrangement at the bed. Further programmes of investigation should therefore incorporate the tracking of bed state changes, in terms both of bed form development and of composition and texture changes.

Studies of individual grain behaviour, such as those reported, represent a reductionist approach that may be untenable in terms of prediction procedures for practical outcomes such as natural morphology and the response to engineering interventions. However, given that parametrization on the basis of dimensional or stream-scale physical arguments has signally failed to produce results of general reliability, close re-examination of the physics of grain–fluid interaction is justified. It should assist in improving the theoretical background of prediction methods that themselves deal with variables of collective grain behaviour, and in resolving some of the apparent anomalies in the existing library of data sets. Methods of measurement of grain transport rate, of bed composition and structure, and of near-boundary flow velocity are all currently improving so that better resolution will be achievable in future in the validation of proposed formulae.

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