The dynamics and morphology of river dunes: synthesis and future research directions

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Abstract
Progress in understanding the dynamics and kinematics of alluvial dunes has been significant in the last 15 years, and has witnessed huge advances in the field, laboratory and numerical investigation of river dunes. Such research now provides an outstanding background for beginning to address areas of great complexity that will enable a fuller understanding of these important natural features. Six areas are highlighted as the possible focus for future research: i) the influence of dune leeside angle, ii) the influence of 3-dimensionality in dune shape, iii) bedform superimposition and amalgamation, iv) linking sediment entrainment and transport to the coherent flow structures generated by dunes, v) the scale and topology of dune-related turbulence and its interactions with the flow surface, and vi) the influence of suspended sediment on the dune flow field and dune morphology. Each of these areas will be discussed in relation to a range of studies from laboratory, field and numerical simulations.

1. Introduction
River dunes are of key importance within many branches of environmental and engineering science in the practical management of contemporary river channels (ASCE, 2002), and adopt especial significance in the sedimentary record where river dunes form the key building blocks of many ancient alluvial successions. Thus an understanding of how the processes of flow over dunes lead to erosion, transport and deposition, and the inverse problem in the rock record of deciphering the sedimentary structure to reconstruct flow processes, is essential to more complete interpretations. However, in order to more fully understand the dynamics of river dunes, a fuller appreciation is needed of the complex links between turbulence, bed morphology and sediment transport. Recent years have seen spectacular progress in our knowledge of dune dynamics that has often been linked to significant advances in our ability to monitor flow and dune morphology in the laboratory and field, and the increasing sophistication of numerical modelling to capture not only the characteristics of the mean flow field but realistically simulate the origins and motions of coherent flow structures above dune beds. These advances in laboratory, field and numerical modelling now leave us, as never before, in a position to make radical progress in quantifying, modelling and understanding the dynamics and kinematics of alluvial dunes.

This talk will present a brief synthesis of recent work concerning the fluid dynamics, morphology and sediment transport associated with river dunes and their key role in generating sequences within the ancient sedimentary record. The talk will then present a personal view in highlighting six areas, listed below, of recent/ongoing and future research that appear vital for a more complete understanding of the dynamics of river dunes.

2. Key issues
i) The occurrence and fluid dynamics of low-angle dunes

Much of our current modelling and research have concentrated on the dynamics of river dunes that have angle-of-repose leesides which generate flow separation and appreciable turbulence downstream (Bennett and Best, 1995, 1996; Kadota and Nezu, 1999; Kostaschuk, 2000; Lyn, 1993; McLean et al., 1994, 1999;

van Mierlo and de Ruiter, 1988; Müller and Gyr, 1983, 1986; Nelson et al., 1993; Shimuzu et al., 1999). Debate still exists as to the nature and cause of low-angle river dunes (Kostaschuk and Villard, 1996, 1999; Best and Kostaschuk, 2002; Best et al., 2004; Wilbers, 2004), and the similarities and differences between the flow fields of high and low-angle dunes. Data from the Jamuna River, Bangladesh, and other large rivers (Kostaschuk et al., 2004) show that low-angle dunes are common and recent laboratory and numerical modelling show the details of flow in the dune leeside, including the possibility of intermittent flow separation and turbulence production.

ii) The influence of dune three-dimensionality

In addition to most past research being concerned with angle-of-repose dunes, virtually all work has concerned dunes that are essentially two-dimensional and have no 3D shape or curvature, a situation that is rare in natural river channels. Recent work by Maddux et al. (2003a,b) has presented the first detailed study of flow over 3D dunes and demonstrated that the nature of the mean flow and turbulence are greatly influenced by dune shape. Maddux et al. (2003a,b) showed that although the friction coefficients of 3D dunes were 50% greater than their 2D counterparts, the turbulence generated by 3D dunes was weaker than the 2D case, due to the generation of secondary flows over the 3D forms. The crestline of many natural dunes is also curved, creating scour troughs in the dune leeside that greatly influence the leeside fluid dynamics. Field observations suggest the occurrence of intense, large-scale turbulence over these 3D forms and highlight the urgent requirement for a fuller analysis of dune three-dimensionality.

iii) Bedform superimposition, amalgamation and the stability of dunes

Records of bed morphology from natural channels show the frequent occurrence of dunes of different scales (ten Brinke et al., 1999; Wilbers and ten Brinke, 2003; Wilbers, 2004), possibly as a response to both non-uniform and unsteady flow, or developing boundary layers on the backs of large dunes. Such bedform superimposition, and subsequent bedform amalgamation due to the fact that smaller dunes often migrate more rapidly, induced substantial changes to the flow field during the processes of amalgamation (Best and López, 1999; Fernandez, 2001). Because of the ubiquitous occurrence of dune superimposition, the nature of the flow fields and bed response must be quantified in these complex geometries.

iv) Linking sediment entrainment to dune-related turbulence

Much work has suggested the link between dune-related turbulence, both in generating erosion at flow reattachment and the dune crest, and sediment suspension due to large-scale vortices generated in the dune lee (Jackson, 1976; Lapointe, 1992; Müller and Gyr, 1983, 1986; Babakaiff and Hickin, 1996). Despite these suggestions, few studies have sought to quantify this relationship (Babakaiff and Hickin, 1996; Bennett and Vendetti, 1997; Vendetti and Bennett, 2000; Schmeeckle et al., 1999) and little is known of the exact links between vortex structure and sediment entrainment. Recent advances in laboratory experimentation, using 2-phase particle imaging velocimetry (PIV), and multibeam echo sounding in the field, will be used to illustrate possible methods for quantifying these links.

v) The scale and topology of dune-related turbulence and interactions with the flow surface

A common observation in natural river channels is the eruption of dune-related turbulence on the flow surface (Figure 1), this generating large-scale upwellings and 'boils'. Laboratory (Müller and Gyr, 1983, 1986; Kadota and Nezu, 1999; Best, 2004) and field research (Jackson, 1976; Babakaiff and Hickin, 1996) has illustrated the link between these vortices and dunes, yet little is known of how these structures approach, and interact with, the flow surface. However, recent research has illustrated the key interactions that may occur between vortex rings with a free surface (Rashidi and Banerjee, 1988; Rood, 1995; Sarpkaya, 1996) and how this may influence the dynamics of the vorticity. Consideration of this literature, and observations of natural river surfaces, provides clues to the topology of dune-induced large-scale turbulence and highlights the possible significance of this interaction. Recent numerical modelling also suggests that Görtler vortices may be associated with bedforms (Zedler and Street, 2001) and that current models that involve primarily flow-transverse vorticity may thus need modification.

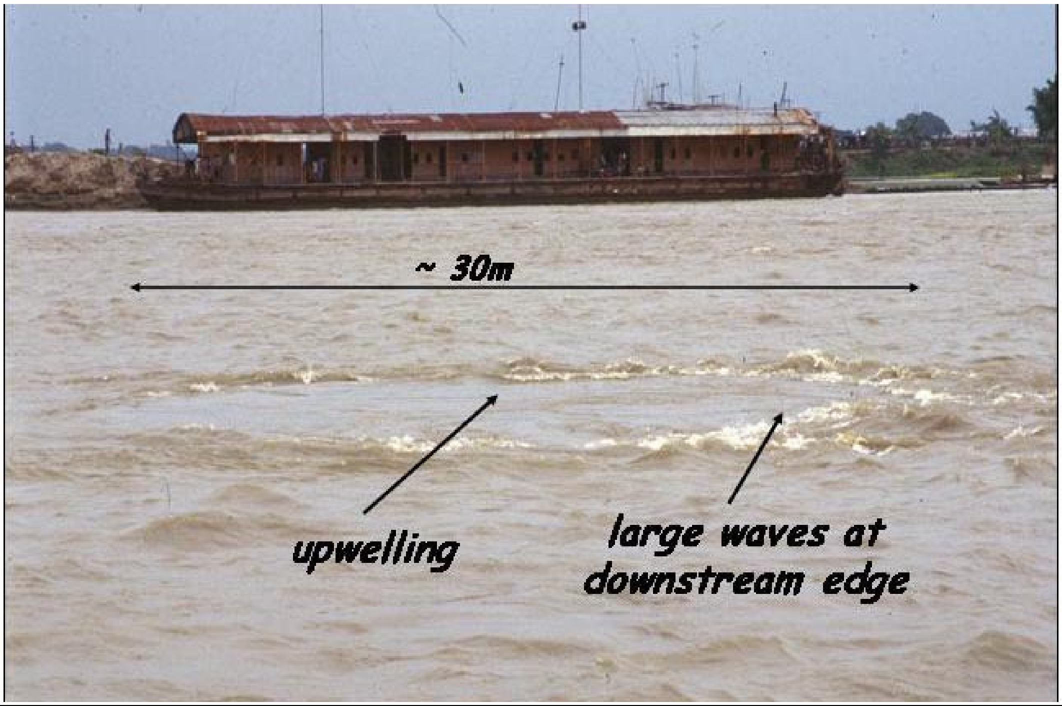

Figure 1: Eruption of large-scale, dune-related turbulence on the flow surface above a field of 2-m high, three-dimensional dunes, Jamuna River, Bangladesh. Diameter of surface 'boil' is approximately 30m and flow is left to right.

vi) The influence of suspended sediment on dune morphology and flow dynamics

Most laboratory studies of dunes, over both fixed and mobile beds, and investigations in the field have examined situations where the water flow is clear or possesses low concentrations of suspended sediment. However, research in the field has also suggested the possible link between sediment suspension and the production of low-angle dunes (e.g. Kostaschuk and Villard, 1996) and laboratory experiments also indicate that at certain clay concentrations the dune morphology may be significantly modified (Wan, 1982). New experimental results using ultrasonic Doppler velocity profiling will be used to demonstrate the significant influence of clay concentration on flow separation in the dune leeside. Since high sediment concentrations are often present in alluvial channels, the links between sediment concentration and turbulence modulation over dunes, and the subsequent effects on dune morphology, require urgent investigation.

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