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Aeolian–fluvial interactions in dryland environments: examples, concepts and Australia case study

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Abstract: Over the past 10 to 15 years there has been a rising interest in interactions between aeolian and fluvial processes from geomorphologists and sedimentologists. This reflects recognition of the limitations of a reductionist perspective examining single process systems in understanding landform and landscape development. This paper focuses on the rise of aeolian–fluvial interaction research in dryland environments. We first explore the background to the contemporary situation then review existing research on aeolian–fluvial interactions at global/regional and local scales. From this review it is suggested that landscape sensitivity, or the effectiveness of links between the process systems, spatial environmental transitions and temporal environmental change are the three main driving forces determining the geomorphological significance of aeolian–fluvial interactions. The importance of the first two of these driving forces is explored in more detail using Australia as a case study. We conclude by highlighting some future possible research directions in this field.

Key words: aeolian, Australia, fluvial, landscape sensitivity, process interaction, scale.

I Introduction

Sedimentary signatures formed by aeolian and fluvial processes have been widely recognized in stratigraphic sequences. Different sedimentary characteristics indicate a change from an environment where aeolian deposition dominates to one where fluvial deposition dominates, or *vice versa*, and play an important role in the reconstruction of palaeoenvironments. The temporal and spatial differentiation of dominant processes is

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not always clear however, and mixed aeolian–fluvial deposits can be identified as can sequences where the interplay of fluvial and aeolian depositional processes is very subtle (Andrews, 1981; Mountney *et al*., 1998). Although attempts have been made to interpret these sequences, few modern analogues are available to assist in this. To establish modern analogues it is necessary to examine current interactions between aeolian and fluvial systems.

There is increasing evidence that understanding aeolian–fluvial interactions at a range of timescales is important not only for reconstructing past climates, but also for understanding aspects of contemporary landscapes such as channel styles and dune morphology. Sedimentological evidence for past aeolian–fluvial interactions is available from most climate zones, however contemporary interactions are most clearly apparent in today's semi-arid and arid environments. The implications of such interactions are not necessarily spatially confined and can attain global significance.

This paper provides first, a brief review of the development of research in aeolian–fluvial interactions during the twentieth century. Following this, we review existing research on aeolian–fluvial interactions at global/regional and local scales. From this review, three key theoretical concepts are identified and discussed, which are common to all scales and which affect the nature and intensity of aeolian–fluvial interactions. The final major section of the paper explores the robustness of two of these theoretical concepts by applying them to aeolian–fluvial interactions operating at a range of scales in Australia.

II The development of research in aeolian–fluvial interactions

The pioneers of dryland geomorphology can broadly be divided into two camps – the 'aeolianists' and the 'fluvialists'. The 'aeolianists' included researchers such as Penck (1905), Passarge (1904) and Keyes (1912) who advocated wind as the dominant process operating in drylands. Keyes (1912) in particular believed:

> . . . beyond all shadow of doubt that as a denuding, transportive and depositional power, the wind is not only fully competent to perform such work, but that it is comparable in every way to water action in a moist climate (Keyes, 1912: 541)

In contrast, those subscribing to the 'fluvialist' school of thought supported the idea that fluvial processes were dominant in drylands (e.g., Davis, 1905; Bryan, 1925, 1936). Cotton (1947) argued that:

> . . . the agent chiefly responsible for the development of most desert landscapes by erosional sculpture and by transportation and deposition of waste is flowing water (Cotton, 1947: 11).

Each perspective has had periods of dominance. Very early work (pre-1880s) was generally fluvialist in nature with the aeolianists gaining prominence in the early twentieth century. The influence of W.M. Davis revitalized fluvialist ideas in dryland research (Davis, 1905, 1930) although following the publication of Bagnold's *The physics of blown sand and desert dunes* (1941) research in many arid regions focused on aeolian processes and landforms. This prompted Reid and Frostick to declare as recently as 1997 that 'until recently the role of rivers in shaping the desert landscape has generally been underestimated' (1997: 205).

As research into Quaternary environmental change in drylands has developed, oscillations between periods of predominantly aeolian activity and predominantly fluvial activity have been recognized. In particular, the work of Tricart (1965) in Niger documents the impact of aeolian–fluvial interactions resulting from Quaternary climate changes on the development of the Niger River and delta and has been cited as 'one of the most eloquent treatments of fluvial–aeolian interaction in the dry tropics' (McIntosh, 1983: 185). Many studies have taken a polarized view contrasting 'arid' phases, when aeolian processes supposedly dominate, with more humid phases, or 'pluvials', when fluvial and lacustrine processes are thought to dominate (Bullard and Livingstone, 2002). However, linking aeolian or fluvial activity to particular climate conditions is often not this straightforward.

Over the past 10–15 years there has been a gradual recognition of the importance of interactions between aeolian and fluvial processes and an increasing number of studies make reference to this. However, whilst there may be 'many more areas where the interplay of domains is dominant than areas where one process holds exclusive sway' (Cooke *et al*., 1993: 8), it is still the case that, although links between aeolian and fluvial systems are often invoked to explain landform and landscape development, their interaction is rarely the dominant subject of investigation in geomorphology. There are several reasons why this might be the case. Cooke *et al*. (1993) state that it can simply be more 'convenient' to identify two key process domains – the aeolian and the fluvial. This is especially likely when the timescale of interest is short. In addition, the natural variability of both aeolian and fluvial processes in dryland environments makes the logistics of monitoring and measuring interactions between them challenging (Bullard and Livingstone, 2002).

Although field process studies of contemporary interactions are still very rare, there has been a recent surge of interest in aeolian–fluvial interactions. For example, an International Geological Correlation Programme (IGCP-413) symposium held as part of the 15th International Union for Quaternary Research (INQUA) Congress in 1999 featured several papers that considered long-term relationships between arid and humid records and events in dryland regions (Thomas and Singhvi, 2002). More explicit discussion of aeolian–fluvial interactions was the subject of a workshop focusing on interactions between fluvial, lacustrine and aeolian processes in October, 2000 (Zzyzx, California) and a number of papers on the topic have been presented at recent international conferences (Bourke, 2001; Bristow, 2001; Maroulis and Nanson, 2001; Sweeney and Loope, 2001; Stollhofen *et al*., 2001). Given this rise in interest in the topic, it is an opportune time to review our current theoretical and empirical understanding of interactions between aeolian and fluvial systems in drylands.

III Spatial scales of interaction

The relationship between process systems varies according to the scale at which it is considered. There are locations where fluvial activity has an impact on aeolian processes and landforms and those where aeolian activity triggers a response in the fluvial regime, as well as areas where the two systems are co-dependent.

1 Global and regional scale

At a global scale the major controls on fluvial activity are climate and topography (including tectonism and geology). Aeolian activity is also determined by climate, although areas dominated by aeolian landforms are not necessarily those where wind energy is the greatest but are those characterized by a suitable sediment supply and usually a lack of vegetation, in addition to suitable wind conditions. At a global scale fluvial activity is not strongly influenced by aeolian systems but key areas of aeolian activity can be closely related to fluvial systems. This unequal relationship stems from the importance of fluvial transport in supplying and sorting sediment. The size selectivity of the wind as an agent of sediment transport means that, although rock weathering and hillslope transport processes can supply small amounts of sediment direct to the aeolian system, the majority is made available through the sorting and concentrating action of fluvial channel transport or from pre-worked aeolian deposits (Smith, 1982; Pye and Tsoar, 1990; Bullard and Livingstone, 2002).

In contemporary aeolian systems there is a fundamental difference between the behaviour of fine sediments (dust-sized material <100 μm) and coarser sediments (sand-sized material 63–500 μm). Dust-sized material is transported in suspension at a wide range of heights above the surface and can rapidly travel considerable distances. Dust plumes disperse as they travel away from source diffusing the concentration of sediment. Consequently, although there are clearly definable sources for dust emissions these finer particles can be transported around the globe and their deposits can be far removed from source areas and very extensive (Shinn *et al*., 2000; Ozsoy *et al*., 2001). For particular locations to be permanent or sustained sources of dust-sized material there has to be a continued supply of fine sediments to the emission areas to replenish what has been removed by the wind. In contrast sand-sized material predominantly travels by saltation, reptation and surface creep within the lowest levels of the atmospheric boundary layer (<3 m above the surface) and travels comparatively short distances. Sand-covered surfaces promote further sand accumulation and, provided that sediment input exceeds output, a dunefield (<30 000 km^2) or sand sea (≥30 000 km^2) can develop. These are usually located within clearly defined areas which may be bounded by topographic barriers or vegetation.

The difference in behaviour between finer and coarser aeolian sediments is reflected in the relationship of aeolian systems to fluvial systems at the global scale. A detailed analysis of global dust sources by Prospero *et al*. (2002) demonstrates that all major contemporary dust sources are identified with topographic lows in areas with an annual rainfall less than 250 mm. These areas are predominantly located within internally draining basins with seasonally active rivers, streams and playas. The alluvial material deposited within these channels and on the floodplains following flood events is a major source of dust. In some cases deep alluvial deposits laid down during the Pleistocene are also dust sources (Prospero *et al*., 2002). Where currently active ephemeral streams are major sources of dust, a temporal relationship between fluvial events and dust events can be discerned (McTainsh *et al*., 1999). If the supply of fine materials to dust source areas is not maintained the magnitude and frequency of dust events diminishes (e.g., Clarke and Rendell, 1998).

The global relationship between sand seas or dunefields and fluvial systems is more complex than that for dust source areas. The large quantities of sediment needed to create a sand sea take considerable time to accumulate. This means that other variables operating over long periods of time, such as tectonic activity, can affect the development of sand seas, for example by affecting fluvial gradients, base levels and sediment supply (Winspear and Pye, 1995). In addition, topography can play an important role in providing the accommodation space for a sand sea to develop and in promoting a suitable wind regime for aeolian deposition (Wilson, 1971; Fryberger and Ahlbrandt, 1979). In many sand seas fluvial activity has played an important role in the accumulation of sand deposits but in older dunefields there may no longer be a clearly defined fluvial input of sediment owing to channel changes by tectonics, climate change or migration of the erg away from the original source of material. Many sand seas and dunefields are thought to have been sourced primarily by fluvial systems including the major Australian dune deserts (Pell *et al*., 1999, 2000, 2001), the Egyptian sand sheets (Embabi, 1998), many of the dunefields in the USA (e.g., Smith, 1982; Lancaster, 1995; Muhs *et al*., 1995) and, indirectly, the Namib Sand Sea (Corbett, 1993).

At the regional scale, interactions between aeolian and fluvial systems take place within dunefields, sand seas or catchments. In particular, aeolian–fluvial interactions can affect the extent, shape and boundaries of an individual dunefield. Perennial or ephemeral rivers can act as interceptors of sediment blocking the downwind movement of sand. For example, the perennial Orange River marks the downwind margin of the southwest Kalahari dunefield (Thomas *et al*., 1997), the Colorado River defines the downwind edge of the Algodones dunefield in southern California (Sweet *et al*., 1988) and the dunefields in northern Sudan terminate at the River Nile. Sand seas bordered by ephemeral rivers include the Wahiba Sand Sea, which terminates at the Wadi al Batha (Warren, 1988) and the Namib Sand Sea, the downwind margin of which ends in the Kuiseb River.

2 Local scale

In drylands, aeolian–fluvial interactions also occur at the scale of individual landforms. Possibly the most common landform to result from aeolian–fluvial interaction is the source-bordering dune, one of the main requirements for which is a regular source of sand from a seasonally flowing sand-bed channel (Williams, 1994). Source-bordering dunes have been described alongside rivers in Australia (e.g., Twidale 1972; Bowler, 1978; Nanson *et al*., 1995; Page *et al*., 1996), the Taklamakan Desert, China (Zhu *et al*., 1987), north America (Carver and Brook, 1989; Markewich and Markewich, 1994) and many other areas. They develop when sand from the channel bed is deflated and deposited adjacent to the channel forming a dune transverse to the main wind regime and usually parallel to the channel. Lunette dunes can also be considered source-bordering dunes. These form downwind of pans and playas and have been widely described in arid and semi-arid environments (Goudie and Wells, 1995 provide a recent summary of research). The modification of wind regimes by fluvial landforms can also affect aeolian processes. The topography of a valley can have a significant impact on wind strength and direction, affecting the distribution of sediments and consequently dune morphology (Bullard and Nash, 1998, 2000; Bullard *et al*., 2000)

The relationship between aeolian and fluvial systems is not restricted to the fluvial supply of sediment to aeolian systems, sediment removal can also be important. Fluvial erosion is usually concentrated around the base or plinths of dunes as water flows along interdunes or where dunes have encroached onto drainage paths. In Langford's (1989) study of aeolian–fluvial interactions he found that when interdunes were inundated, the flood waters rose until water overtopped the enclosing dunes or flowed through the dune sand causing sapping. The temporary interdune pond or lake would then drain over the dune, partially filling the adjacent interdune and incising a channel through the dune. Harrison and Yair (1998) found that, following a series of flood events, the margins of interdune playas in the Nizzana dunefield, Israel, were eroded leaving the central areas as positive landscape features, isolated from surrounding linear dunes. Fluvial channels erode the lower flanks of dunes but rills and small streams can also form on dune slopes themselves, especially if the dunes are fixed, partly consolidated or have a surface crust. For example, Talbot and Williams (1978) describe alluvial fans forming on flanks of fixed dunes in central Niger. The alluvial fan sediments come from headward extension and overland flow-induced scour across the upper ungullied parts of dunes. This process entrains any loose wind-deposited material that has been accumulated. The aeolian deposits are reworked by the water flow and then redeposited in alluvial fan forms causing the dunes to degrade (Talbot and Williams, 1978).

Some source-bordering dunes are extensively gullied by water erosion. These may be part of a sediment cycle whereby the aeolian sands comprising the dune are eroded by water which flows back into the fluvial or lacustrine source area (Wopfner and Twidale, 1988). Thomas *et al*. (1993) identified such a sediment cycle operating at Witpan, south-western Kalahari, in which sediments from the pan floor are deflated and incorporated into a partially active lunette dune on the downwind pan margin. During storm events, gullies on the lunette dune are activated and the sediments are transported back to the pan floor by the runoff. These sediments then become available once again for deflation, continuing the cycle.

The rate and nature of sediment supply to aeolian systems from fluvial systems is not only a function of sediment production and sorting but is also strongly dependent upon the nature of the channel via which sediment is transported. Flow regimes where low or zero flow is common and channels which are wide, shallow or braided are more likely to be sites of deflation than deep, narrow channels or those which have perennial or near-perennial flow. Muhs and Holliday (1995) developed a process–response model to summarize the relationship between climate change and fluvial and aeolian activity in the Great Plains, USA, which associated the formation of wide, braided channels with periods of increased aeolian activity (Figure 1). Lancaster (1997) also found that periods of aeolian construction in the Coachella Valley, south-central California were determined by stream channel dynamics, however, at this site, increased sediment supply is associated with periods of channel entrenchment. Sediment is supplied to the dunefield via alluvial fan complexes. During periods of increased rainfall and storm intensity, channels on the fans become entrenched and sediments entrained during this process are transported to the distal areas of the alluvial fans, close to the dunefield. Once the channel entrenchment ceases and aggradation starts, the quantity of sediment carried to the edge of the fans is reduced resulting in a change in dunefield activity from sediment accumulation to dune modification and degradation.

The above examples demonstrate that the channel style and flow regime of a river can affect aeolian activity but there is also evidence to suggest that this is not a one-way

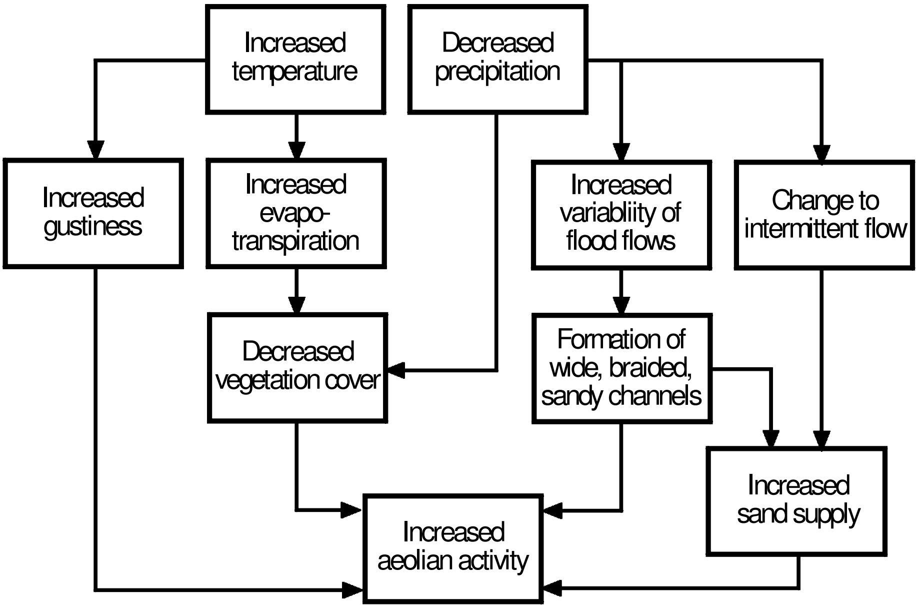

Figure 1 Muhs and Holliday's (1995) process–response model of climate change and fluvial and aeolian activity in the Great Plains, USA
Source: reprinted from *Quaternary Research*, Vol. 43, Muhs, D.R. and Halliday, V.T., 'Evidence of active dune sand on the Great Plains in the 19th century from accounts of early explorers', pp. 198–208, © (1995), with permission from Elsevier

relationship. Sediment–water ratio has a significant impact on the morphodynamic characteristics of rivers. Aeolian activity could increase the sediment loading of a river such that it changed from a meandering to a braided style. Arctic rivers in Canada have been observed to develop braided channels when crossing dunefields but there are few reports of such changes in contemporary dryland environments. Stratigraphic studies lend some support to this hypothesis. Huisink (2000) found a close correspondence between changes in river type and aeolian activity from the Middle Pleniglacial to the Holocene. Low-energy meandering rivers were associated with periods of low aeolian activity and high-energy braided systems were associated with periods of high aeolian activity. It is unclear, however, whether the change in channel style was caused by an influx of sediment resulting from aeolian activity or whether warmer conditions led to a decrease in vegetation density and bank stability. Finer sediments can also have an impact on channel style by increasing suspended sediment load (Fried, 1993) or affecting flocculation and consequent conversion of sediments from suspended load to bedload (Rutherford and Ellaway, 1988).

Other effects of aeolian activity on fluvial systems include diversion and damming of rivers (Mason *et al.*, 1997), narrowing or constriction of valleys (Marker, 1977), channel avulsion (McIntosh, 1983; Jacobberger, 1988; Jones and Blakey, 1997; Bourke and Pickup, 1999) and bifurcation (Tooth, 1999) and waterhole development (Knighton and Nanson, 1994). Ephemeral rivers can be blocked or diverted by sand dunes. Several rivers draining from east to west in the central part of the Namib Sand Sea, e.g., the Tsondab and Tschaub, have been blocked by aeolian sand dunes in the past (Teller and Lancaster, 1986). Urvoy (1942) and Tricart (1965) describe a succession of dunes which blocked the flow of the Niger River during dry phases, causing the formation of large upstream lakes which then breached the dune dams during more humid periods. Star dunes have blocked the drainage of alluvial fans in Panamint Valley, California (Anderson and Anderson, 1990) and Jones and Blakey (1997) report a stairstep series of four barchan dunes damming a single alluvial fan drainage channel at Great Sand Dunes National Monument, Colorado.

Loope *et al*. (1995) found that dunes in the Nebraska Sand Hills became more active during drought-enhanced periods of Holocene aeolian activity (10 000 BP, 4300 BP and post-1500 BP). Precipitation was sufficiently reduced to enable aeolian sediments to block fluvial valleys leading to the development of approximately 1000 interdune lakes over an area 7000 km^2. They suggest that the shape of interdunes can be an important determinant of the effectiveness of the dunes as dams – elongate interdunes parallel to the underlying topographic gradient are associated with less effective dune dams. Similar studies of aeolian–fluvial interactions in Israel by Harrison and Yair (1998) also associate the formation of interdune lakes with periods of aridity.

IV Temporal scales of interaction

Temporal variations in the nature and intensity of aeolian–fluvial interactions also operate at a range of scales and are controlled by changes in the flow regimes of air or water and in sediment supply and availability. In the Quaternary record, there have been periods when wind velocities have been greater and less than at present. The expansion of continental ice at the poles caused an increase in pressure and temperature gradients between the equator and high latitudes, which resulted in an increase in trade wind velocities (Parkin, 1974). Although regionally variable, in dryland areas glacial periods were times of widespread aridity and consequently glacial maxima are frequently associated with drier, windier conditions. Conversely, interglacials are associated with wetter conditions. There is considerable geomorphological evidence to support a generalization of this pattern (e.g., Williams, 1985). Evidence from the Greenland ice cores indicates a strong relationship between the presence of high concentrations of alkaline dusts and cold periods, although not all dusts are aeolian in origin (Taylor *et al*., 1993a,b). Whilst these broad relationships between long-term climate change and aeolian or fluvial activity in drylands are widely recognized, such generalizations disguise considerable local variation caused when, for example, changes in temperature and precipitation are not synchronous (Kershaw and Nanson, 1993).

Temporal variations in aeolian or fluvial activity also occur at much shorter timescales. In particular, relationships between rainfall and the El Niño–Southern Oscillation have been recognized as having an impact on geomorphological processes in many dryland areas. For example, changes in the Walker circulation associated with phases of the Southern Oscillation have been linked to an 18-year rainfall cycle operating in parts of southern Africa (Lindsay *et al*., 1986). Bullard *et al*. (1997) demonstrated that such temporal variations in rainfall have a marked influence on the activity of linear sand dunes in the southwest Kalahari desert. In Australia, major flood events in the arid Channel Country region are clearly associated with La Niña phases of the El Niño–Southern Oscillation phenomenon (Kotwicki and Allan, 1998).

In addition to decadal fluctuations, many dryland regions are characterized by strongly seasonal variations in wind strength and rainfall. For example, in the Namib Sand Sea the amount of potential aeolian sand transport varies seasonally and with location. Near the coast the maximum potential sand drift is November–February, whereas further inland the peak is more variable and can occur during the austral winter (Lancaster, 1985). At one coastal location Lancaster (1985) found that 80% of potential sand movement could be attributed to winds blowing for only 6% of the time. The relative magnitude, frequency and timing of rainfall events and sand-transporting winds is important in terms of the interaction between fluvial and aeolian processes. For example, Keyes' (1912) work in the southwest USA suggested that

> Under conditions of aridity the relative efficiencies of wind-scour and water action may be roughly measured by the circumstance that the total volume of rock-waste brought down by storm waters from a desert range in a year may be removed by the winds in a single day (Keyes, 1912: 541).

In contrast, in the Namib Sand Sea, dunes advance into the Kuiseb valley near Gobabeb extending approximately 2 m per year (Ward, 1983), yet annual flood events travelling down the river can remove this sand and prevent the dunes from blocking or crossing the valley (Goudie, 1972).

In cases where fluvial and aeolian activity are not flow- or transport-limited, the key control on the temporal variation of aeolian–fluvial interactions is the availability and supply of sediment. The impact of humid and arid climate phases on sediment production, availability and transport has been considered by Kocurek and Havholm (1993), Kocurek (1998) and Kocurek and Lancaster (1999) who examined the ways in which these factors interact to determine the response of dry systems (Figure 2). In Kocurek's (1998) generic model sediment production peaks during humid conditions owing to enhanced weathering and fluvial sorting and transport, but sediment availability and transport capacity are both low because of vegetation. As conditions become more arid, sediment production declines and sediment availability and transport capacity increase. The cumulative geomorphological effects of these changes in the aeolian system result in stable conditions during humid phases and periods of dune growth and sediment accumulation in the early stages of an arid phase. If arid conditions persist, the system will become sediment-starved because of the lack of sediment production and dunes will be reworked or destroyed by continuing wind action (Kocurek, 1998).

Kocurek and Lancaster (1999) applied this model to examine the sediment budget of the Mojave Desert Kelso dunefield. The Mojave River is the main sediment source for this dunefield, the fluvial sediment load is determined by tectonic activity and discharge is determined by climate. Combining records of fluvial sedimentation rate and flood frequency since 20 ka BP (sediment supply) with contemporary estimates of sediment transport capacity and sediment availability, Kocurek and Lancaster (1999) demonstrated a close relationship between high stands of Lake Mojave and periods of aeolian construction in the Kelso dunefield. Although the model was designed to be applied to long timescales it could also be adapted to shorter timescales in situations where fluvial and aeolian systems are closely coupled. For example, where seasonal

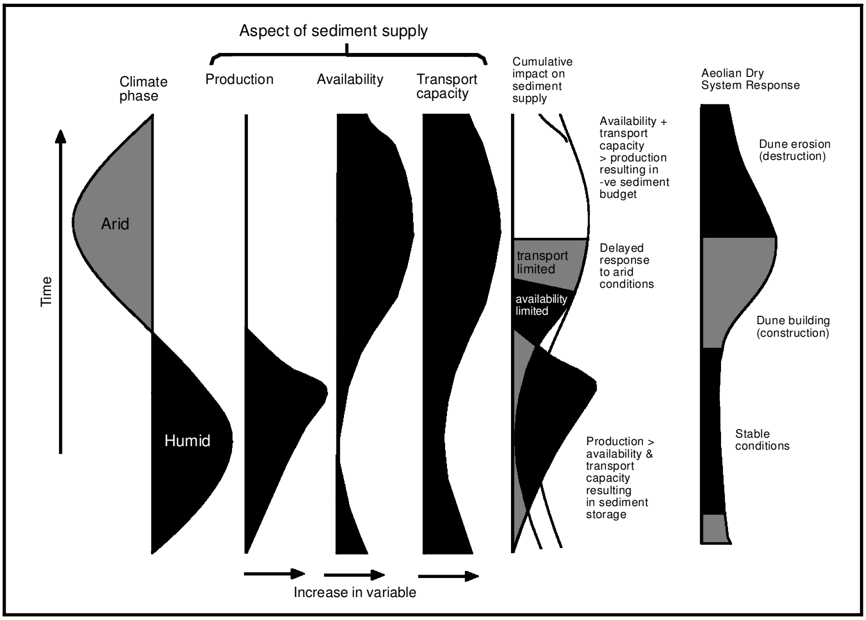

Figure 2 Model of the impact of climate phases on sediment production/availability and transport and the response of the aeolian dry system
Source: modified from Kocurek, 1998 © Swets & Zeitlinger.

rivers deliver an influx of sediment which is subsequently deflated (Williams and Lee, 1995).

V Concepts and issues in aeolian–fluvial interactions

The ways in which fluvial and aeolian processes interact, and the landforms produced by such interactions, are controlled by a number of factors. Langford (1989) attributes the variability of aeolian–fluvial systems primarily to dune morphology, time and depth of the water table. Bullard and Livingstone (2002) suggest that the three main factors controlling the transfer of sediment between aeolian and fluvial systems are moisture availability, the nature of the sediment supply (including sediment load, transport, availability, size and sorting) and the magnitude–frequency characteristics of both fluvial and aeolian events. When these factors are combined and incorporated into temporal and spatial frameworks it is apparent that there are three main driving forces determining the geomorphological significance of aeolian–fluvial interactions: (1) landscape sensitivity and coupling; (2) spatial environmental transitions; and (3) temporal environmental changes. In this paper, we will concentrate on the first two of these driving forces. The third, temporal environmental changes, is a vast topic to which we cannot do justice within the confines of this paper. We will, however, briefly consider the extent to which spatial environmental transitions are affected by long-term climate change in Section VI.

1 Landscape sensitivity and coupling

The response of geomorphic systems to environmental changes can be described in terms of landscape sensitivity (Brunsden and Thornes, 1979). This is a measure of the capacity of systems to absorb, resist or respond to changes in controlling factors such as moisture availability, sediment availability or transport capacity. The sensitivity of the landscape is largely determined by its internal connectivity – the density and strength of links between different parts of the geomorphic system. Brunsden and Thornes (1979) describe two extremes of geomorphic system, the first comprises highly sensitive, fast-responding subsystems which react quickly to external changes, the second is a slow-response insensitive system with poorly developed connectivity.

The concept of 'coupling' or internal connectivity between different parts of the system can be usefully applied to aeolian–fluvial interactions. In this case we are considering not just the aeolian system or the fluvial system and overall sensitivity is determined by the spatial and temporal links between the two systems. Brunsden (1993) identified three coupled states. Where there are no links between component parts of the system he describes it as 'not coupled'. If energy and materials (in this case air, water and sediment) can move freely between the components they are described as 'coupled'. The final state, 'discoupled', applies to landscape units which have previously been coupled but are no longer linked. From our discussion of aeolian–fluvial interactions it is clear that at global and regional scales the relationship between dust source areas and internally draining lowland basins indicates a closely coupled system. At the local scale, sediment cycling on source-bordering dunes such as that described by Thomas *et al*. (1993) represents a coupled geomorphic state with a high degree of interdependence between processes. A degrading dunefield that has been cut off from its fluvial sediment supply e.g., by drainage diversion, may exemplify a discoupled system. Where fluvial and aeolian systems are not coupled, no aeolian–fluvial interactions take place.

The magnitude–frequency characteristics of sediment transfer between systems determines the temporal aspects of coupling and there may be temporary storage/removal cycles within the coupling zone (Harvey, 2001). For example, aeolian sediment may be deposited and stored in ephemeral channels as a result of low-magnitude, high-frequency events and eroded by a single high-magnitude, low-frequency flood event during a wet season. At a longer timescale storage–removal cycles can be related to the interaction of phases of sediment production, availability and transport capacity (Kocurek, 1998).

2 Spatial environmental transition

Sediment production is often related to humid periods and sediment then becomes available to the aeolian system during arid phases. However, changes from humid to arid conditions do not necessarily require temporal changes in climate, they can also occur spatially. Considerable variation in downstream flow conditions can arise in extensive catchments because of flow transmission and seepage losses, water table effects and the impact of antecedent conditions. In particular, large drainage basins can cover a range of latitudes or climates such that sediments produced in the humid tropics may be transported within the basin and, when flow competence is reduced and sediments deposited, may be deflated from more arid areas (McTainsh, 1985). When considering the dichotomy of the aeolianist and fluvialist schools of thought, Cooke *et al*. (1993: 15) noted that 'The dilemma of the extremists is neatly illustrated by the case of the large enclosed basins in many deserts, for which the only acceptable model must be one of interaction, over long periods of time of aeolian, fluvial and, probably tectonic activity'. The spatial environmental transitions that occur within these drainage basins can give rise to close interaction between fluvial and aeolian processes as evidenced by the global relationship between distal areas of channel systems and dust emissions. Spatial environmental transitions can also be manifest at smaller scales. Brunsden and Thornes (1979) suggest that the development of a floodplain reduces the coupling between channel and slope inputs possibly even to the extent that they are not coupled. In dryland environments, however, the floodplain is often what enables the coupling of aeolian and fluvial systems.

VI Aeolian–fluvial interactions in Australia

The penultimate section of this paper explores the range of aeolian–fluvial interactions in Australia within the two theoretical frameworks of coupling and spatial environmental transitions. We provide a broad overview of fluvial and aeolian activity at the continental scale before considering two regions – the Lake Eyre Basin and the Murray-Darling Basin – in more detail.

1 Continental scale

At the continental scale, controls on aeolian–fluvial interactions in Australia reflect those observed globally. The main controls on fluvial activity are climate and topography. The rainfall pattern shows a concentric increase from an inland low between Birdsville and Oodnadatta towards the east and north coasts. The zone of low rainfall (<300 mm) extends to the west and south coasts (Figure 3). In topographic terms, the continent has been divided into three structural regions (Dury, 1968), each of which has distinctive river systems (Figure 4). The Eastern Highlands create a narrow zone of small coastal rivers with relatively high total discharges draining into the Tasman and Coral Seas (North-east and South-east coast systems). The East Australian Basins comprise two major river basins in Australia – the Murray-Darling and Lake Eyre Basins – with relatively low total discharges, separated by the small Bulloo-Bancannia Basin and extending to the coast at the Gulf of Carpentaria. The Western Australian Shield is a large area with no co-ordinated drainage, with coastal drainage in the northwest off the Kimberley Plateau to the Timor Sea, and further south into the Indian Ocean. By excluding the coastal rivers, which are less relevant to the present discussion, the continent can be divided in half. The fluvially active east comprises the Lake Eyre and Murray-Darling Basins, which drain inland from high to low rainfall regions (Figure 4). The fluvially inactive west has only uncoordinated drainage of the Western Plateau which lies within the 300-mm isohyet.

The spatial patterns within the 3 070 000 km^2 of continental dunefields in Australia can be understood by taking into account their climatic and fluvial geomorphic

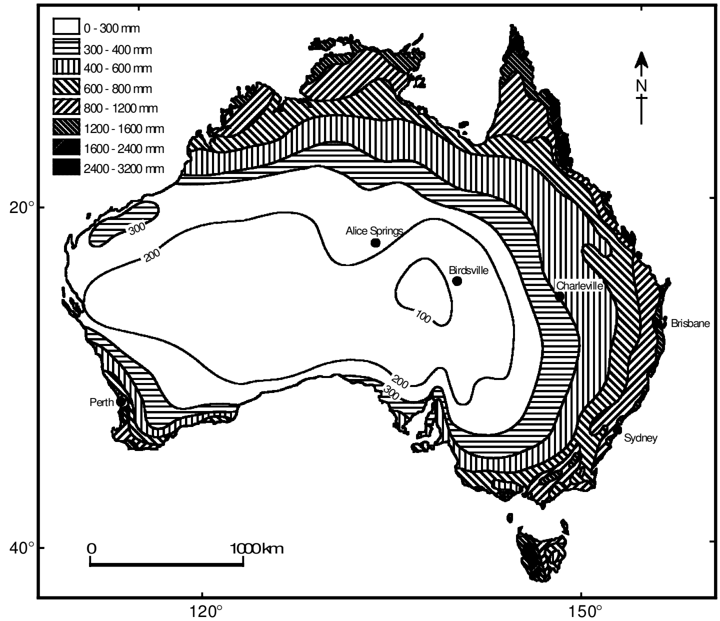

Figure 3 Rainfall isohyet map of Australia
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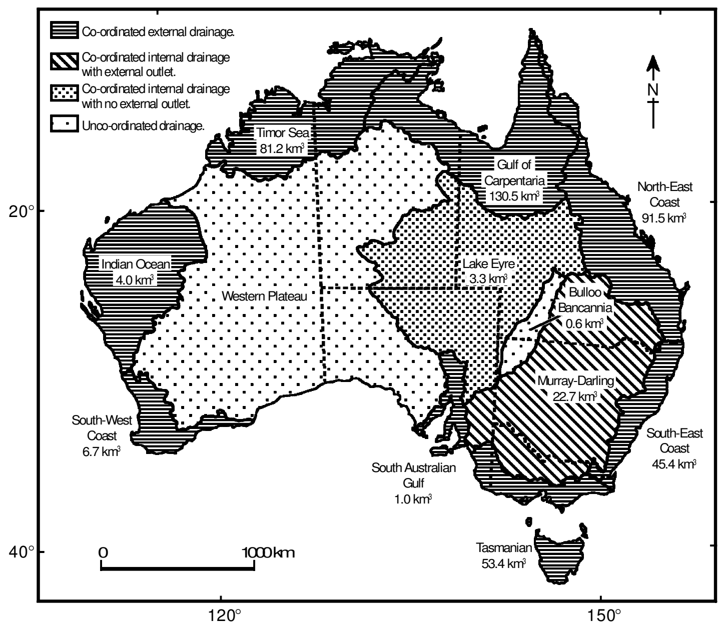

Figure 4 Drainage divisions of Australia
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settings. Comparison of Figures 3 and 5 indicates a clear relationship between dunefields and aridity. The relationship with fluvial systems is, however, more complex and less well-documented. At a generalized level of analysis the relationship may not even be apparent. For example, Wasson *et al*. (1988) estimate that 45% of the continental dunes are found in catchments with organized drainage and the remaining 55% occur in areas of disorganized or uncoordinated drainage.

Although over 50 academic papers have addressed the question either directly or indirectly, the exact nature of the relationship between the Australian continental dunefields and fluvial or lacustrine sediment sources is still unclear and is the subject of sustained and recent debate (e.g., Pell *et al*., 1999, 2000; Wopfner and Twidale, 2001). There is general agreement that fluvial processes have played a role in the delivery and accumulation of dunefield sediments but differences arise in interpreting the spatial and temporal relationship between the dunes and the fluvial systems, sediment characteristics and the roles of aeolian sediment transport and weathering in shaping the dunefields.

What is clear, however, is that the Simpson Desert, the largest and best developed dunefield in Australia, has a clear spatial relationship with the distal end of the Channel Country rivers, the most active river system in the Lake Eyre Basin. Conversely, the Gibson, Tanami and Great Sandy Desert on the Western Plateau region of uncoordinated drainage (Figure 4), while extensive, are of subdued dune relief, which may reflect the reduced fluvial sediment supplies to this region. These dunefields probably developed from the alluvium of ancestral river systems, but they have been sediment supply-limited during the Quaternary (e.g., Pell *et al*., 1999).

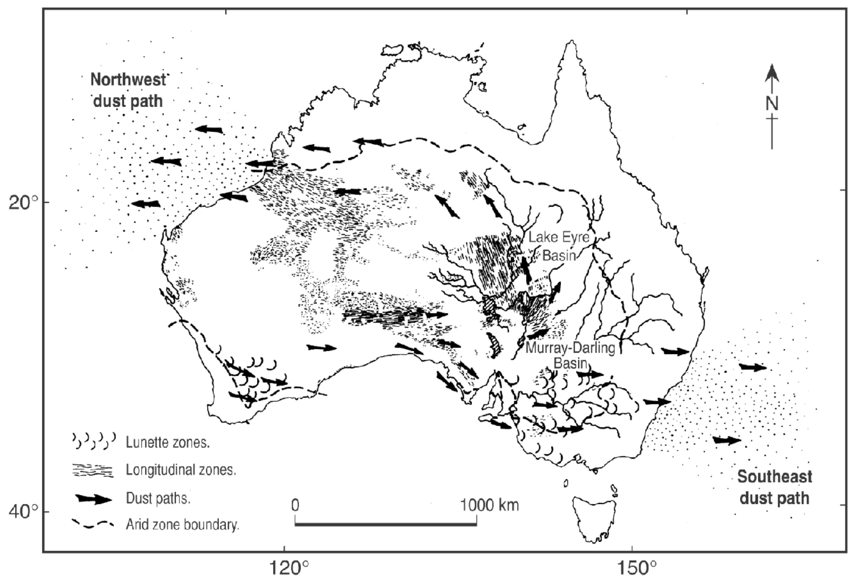

Figure 5 Dunefields, dust pathways and drainage basins in Australia
Source: modified from Bowler, 1976 by McTainsh, G. and Boughton, W.C., editors, *Land degradation processes in Australia 1E*, with the permission of Pearson Education Australia Pty Limited. Copyright 1993.

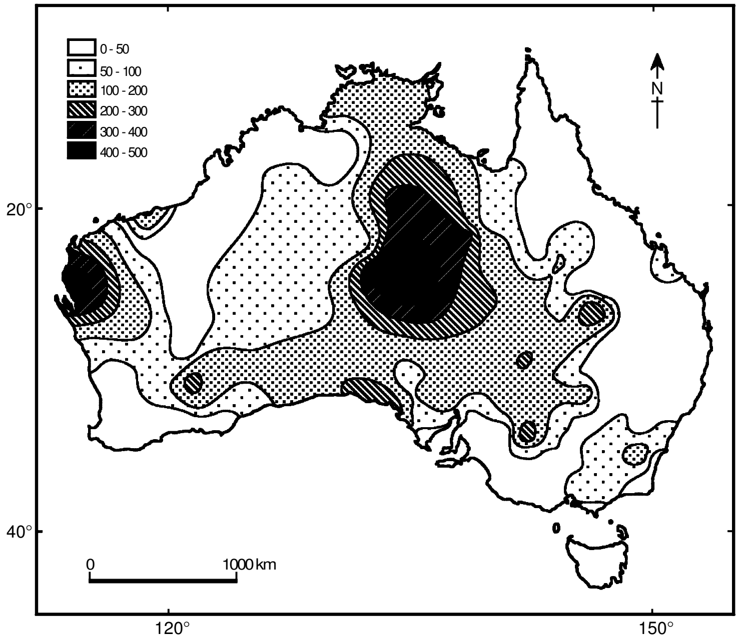

Figure 6 Map of dust storm frequencies

Applying the global relationship described by Prospero *et al*. (2002) between dust source areas and topographic lows with <250 mm rainfall, we would expect the Lake Eyre Basin and Murray-Darling Basin to be the major dust source areas in Australia. A map of dust storm activity (1960–2000) in Australia (Figure 6) shows that the main region of dust activity does in fact coincide with the Lake Eyre Basin and western Murray-Darling Basins. The lower sections of these river basins are the source regions for the two major dust pathways in Australia, first identified by Bowler (1976) (Figure 5) and studied by McTainsh and colleagues (e.g., McTainsh, 1989; McGowan *et al*., 2000).

The negative relationship between rainfall and dust storm activity is evident in Figure 7. A closer inspection of this Figure, however, reveals that a number of stations with low rainfall have low levels of dust storm activity. A large proportion of these stations are in the Western Plateau Region of uncoordinated drainage (mean of 25 dust storms yr^{-1}), whereas the majority of the stations with high dust storm frequencies are located in the more fluvially active Lake Eyre Basin (mean of 82 dust storms yr^{-1}).

2 Regional and local scale interactions: the Lake Eyre Basin

a Fluvial systems and dune systems: The Lake Eyre drainage basin covers an area of 1.14 million km^2 (Kotwicki, 1986) and is characterized by internally draining ephemeral streams and extensive aeolian dunefields (Figure 8). The north and east of the catchment is dominated by three major ephemeral river systems – the Diamantina River, the Georgina River and Cooper Creek, which form part of the Channel Country

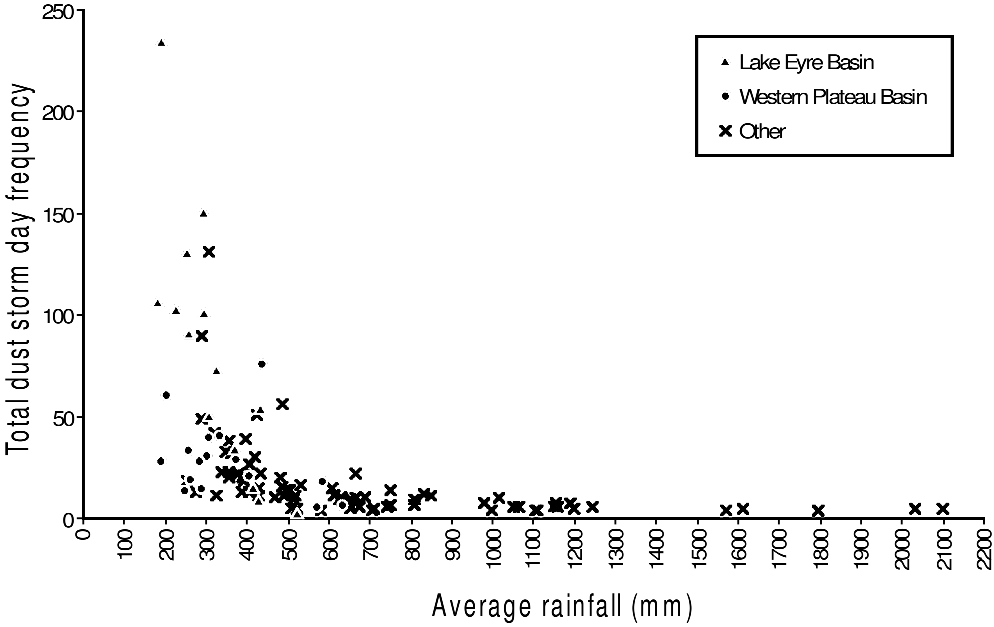

Figure 7 Dust storm frequency versus rainfall graph

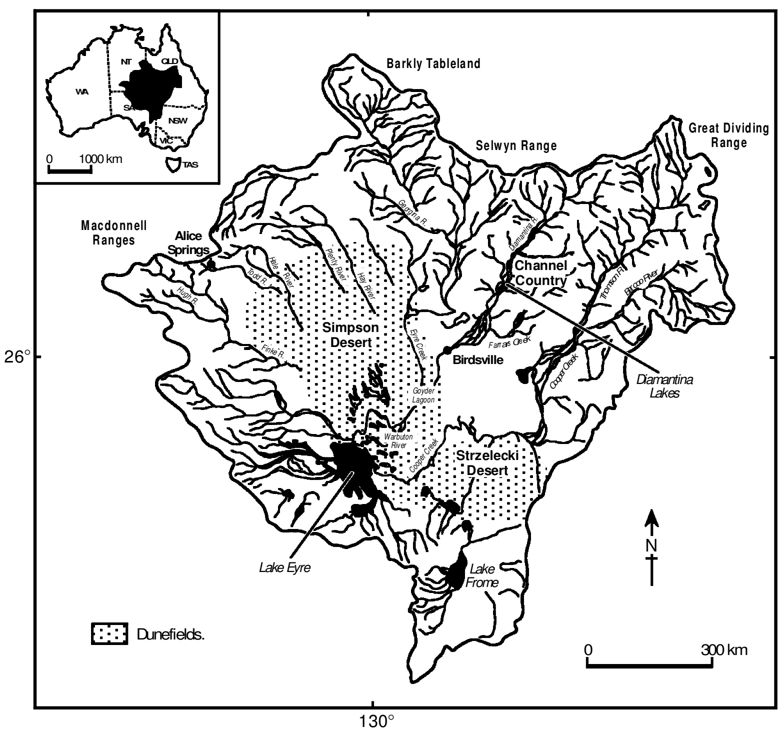

Figure 8 The Lake Eyre Basin

and flow 1000 km south towards Lake Eyre. In the northwest several rivers, including the Todd, Hale, Plenty and Hay, rise in the MacDonnell Ranges and flow south into the Simpson dunefield. Rainfall is highly variable in both space and time. The Channel Country headwaters receive 400–500 mm yr^{-1} of rain and this decreases to 120 mm yr^{-1} in the southwest. Typically most rainfall in the catchment falls between November and March during the Australian monsoon and this intense rainfall results in flooded rivers in most years (Kotwicki, 1986). Transmission losses, seepage and evaporation mean that flow from the Channel Country reaches Lake Eyre only occasionally, the most recent inundation being 1999, whereas that from the northwest rivers dissipates amongst the northernmost Simpson sand dunes.

Several studies have investigated the role of the fluvial networks of the Lake Eyre Basin as suppliers of sediment to the aeolian dunefields. There is general agreement that the dunefields are related to areas of fluvial deposition, however the temporal sequences of fluvial sediment delivery and aeolian dune development are contested (Wopfner and Twidale, 1988, 1992, 2001; Callen and Nanson, 1992; Pell *et al*., 2000; Nanson *et al*., 1992). One crucial aspect of these discussions is whether researchers accept or reject evidence for long distance aeolian sand transport in the region, a process which has itself been variously and poorly defined. Those advocating long distance transport of dune sands have suggested that sediments are cycled between the floodplains and the higher land at the margins of the basin. Sediment is transported by wind onto the high areas and then entrained by runoff and transported via the fluvial system to the more arid floodplains before being deflated once more (Wopfner and Twidale, 1988).

Source-bordering dunes are a distinctive characteristic of the central dunefields in the Lake Eyre Basin. Close-coupling of the fluvial and aeolian systems is evident in local sediment cycles in which sand deflated from the channel bed to form a dune is eroded by runoff and returned to the channel (Wopfner and Twidale, 1988). In many cases, source-bordering channel and lunette dunes merge with linear dunes in the main dunefields and it has been suggested that they reflect multiple sources from which the whole dunefield developed. Twidale (1972) concluded that, based on rates of dune extension from contemporary source areas, the current distribution of fluvial/lacustrine areas could not explain the current extent of the 130 000 km^2 Simpson dunefield. Instead, he linked the development of the dunefield to late Pleistocene pluvial conditions when fluvial and lacustrine areas were more extensive and frequent flooding and renewal of sediment supplies caused dunes to form at multiple sites within the area. Other authors suggest that the dunefield was emplaced earlier than this and that Holocene-dated dunes reflect subsequent aeolian reworking (Nanson *et al*., 1992; Pell *et al*., 2000). Regardless of the precise nature and timing of events, the large scale of the catchment means that an environmental transition from wetter to drier conditions exists and this range of conditions facilitates the production and transport of sediment fuelling interaction between the aeolian and fluvial systems.

Local instances of interaction between aeolian landforms and fluvial channel pattern have been documented in the north of the Lake Eyre Basin. On the Sandover-Bundey River (which links into the Georgina system) the formation of a distributary channel pattern in the river's floodout zone is attributed to the deposition of aeolian sand (dated to 7.1 ± 0.6 ka) across the original channel (dated to 12.9 ± 1.2 ka) causing it to bifurcate (Tooth, 1999). Subsequent flood events have led to the deposition of alluvial sediments on the lower aeolian dune flanks. Similarly, the initiation of a distributary channel pattern by aeolian dunes has been described by Bourke and Pickup (1999) where the Todd River reaches the northern part of the Simpson dunefield. When, during extreme and rare flood events, water flowing in the Todd system reaches the dunefield the channel pattern changes from a single-thread channel to multiple 'trellis-style' channels as the flood waters are confined between the linear dunes (Bourke and Pickup, 1999). Examples of fluvial channels and associated deposits divided by or encircling aeolian dunes have been described elsewhere on the Sandover-Bundey (Tooth, 1999) and within the anastomosing rivers of the Channel Country (Maroulis, 2000).

One distinctive feature of the Channel Country rivers is the presence of permanent waterholes. Knighton and Nanson (1994) found that waterholes tend to form at points of flow concentration, often between aeolian dunes, where a single, sinuous channel cuts down into the floodplain surface. Of 65 major waterholes examined, 35% were flanked on both sides by remnants of aeolian dunes and 23% had either a dune or a floodplain edge on one side. Dune-flanked waterholes are relatively short and wide when compared with those not bounded by dunes and this is attributed to the erodible sandy bank material and limited downstream extents of confining dunes. Knighton and Nanson (1994) suggested that the development of embayments and headlands and the erosion of dunes in the eastern part of the dunefield was evidence that the floodplain and river channels were migrating westward and invading the dunes.

b Fluvial systems and dust transport systems: Figures 5 and 6 indicate that the main dust source region in Australia is the fluvially active Lake Eyre Basin. Using dust storm frequency, the basin can be divided into two regions; the Simpson Desert and the Channel Country. Within the Simpson Desert, the most active dust source region is the southern sector of the desert. Birdsville, on the eastern edge of the Simpson Desert, has the highest dust storm frequencies in Australia (234 dust storms, 1960–2000), and most of the dust storms come from the west. Dust storm frequencies in the northern Simpson Desert are considerably lower – Boulia and Urandangie had dust storm totals of 90 and 104, respectively, during 1960–2000. The Channel Country region has lower dust storm frequencies, for example, Windorah had 50 dust storms between 1960 and 2000.

The southern Simpson Desert is penetrated by two of the three major Channel Country rivers; the Diamantina and Georgina, and this geomorphic setting provides optimal circumstances for dust storm activity: a large supply of alluvial fines, which are readily entrained by the saltation impact of dune sands saltating across the floodplains. The northern Simpson has plenty of dune sands but more limited alluvial sediment inputs because the rivers which penetrate this sector of the dunefield have their headwaters in low rainfall environments. Consequently the rivers carry only a fraction of the sediment of the Channel Country rivers, which arise in the tropical sub-humid environments of north Queensland. In contrast, the Channel Country has plenty of alluvium and the constraint upon dust entrainment is saltating sands. Although there are local source-bordering dunefields in the lower floodplain sections of the Channel Country rivers, their interaction with the floodplains is quite limited, therefore reducing the potential for dust entrainment.

As with dune sands, the close-coupling of the aeolian and fluvial systems may initiate large-scale dust recycling in the Lake Eyre Basin. Figure 5 shows the Lake Eyre Basin is a source region for the two major dust paths in Australia. Dust deposition along the southeast dust path from the Lake Eyre Basin is thought to contribute to the soils of southern Queensland (Hubble and Isbell, 1958) and northern New South Wales (Cattle *et al*., 2001). The northwest dust path is less well understood, but there is present-day process evidence and Quaternary landform and deposit evidence available to suggest that the Simpson Desert–Channel Country sector of the Lake Eyre Basin is also a source region for this dust path. The Sprigg Model of dust transporting wind systems (Sprigg, 1982) suggests that as frontal systems pass over the Lake Eyre Basin, the post-frontal southerlies can entrain dusts from the Simpson Desert–Channel Country region, which enter the northwest dust path.

On 1 November 1994 a large dust storm, driven by southerly winds, transported an estimated 15 Mt of dust (McTainsh *et al*., 1996) from the Channel Country north over Mt Isa and over the Gulf of Carpentaria. As the trajectory of this dust plume was back up the catchments of the Channel Country rivers, a large proportion of the dust load in this plume would have been deposited on the middle and upper catchment lands which are drained by these rivers. There is some Quaternary deposit and landform evidence to support the contention that sediment recycling in the Lake Eyre Basin via the northwest dust path may have been a common occurrence. Using the orientation of the Simpson Desert dunefield as a palaeo-wind direction and therefore dust path indicator (Bowler, 1976), it is apparent that the southerly winds which feed dust into the northwest dust path were active in the Last Glacial Maximum at least. Dust deposits found in palaeo-lake Carpentaria by de Dekker *et al*. (1991) are most likely to have their source in the northern Lake Eyre Basin, which again indicate that up-catchment dust plumes trajectories may have been frequent during the Last Glacial Maximum.

At the local scale some contemporary persectives upon aeolian–fluvial interactions are provided by wind erosion and dust transport studies conducted by McTainsh and colleages (McTainsh *et al*., 1999; Nickling *et al*., 1999) on a clay pan on the high floodplain of the Diamantina River at Diamantina National Park in the Channel Country (Figure 8). McTainsh *et al*. (1999) examined temporal changes (1994–1997) in erodibility of three major land types: high floodplain, dunes and downs. They found that during 1994, a dry year, the erodibility of the dunes was higher than the high floodplain and the downs, but in 1997, a relatively wet year, the erodibility of the high floodplain reached a maximum – far exceeding both other land types. This increase in erodibility was a result of the deposition of erodible fine sands during widespread flooding in early 1997. The highest rates of dust entrainment occurred within one month of the flood peak indicating a closely coupled sediment transfer system.

Data are also available on local aeolian–fluvial sediment recycling elsewhere in Diamantina National Park. A local dust entrainment event on 19 July 1996 on the clay pan section of the western high floodplain of the Diamantina River produced very high local dust concentrations (85 861 $\mu g\ m^{-3}$ at 2 m) and deposition rates (16.7 $t\ km^{-2}$). As the main channel floodplain of the Diamantina River was <2 km downwind of the clay pan source area during this event, deposition onto the river would have been significant. Conservatively assuming that the deposition rate over the river was half that on the clay pan, and estimating the downwind area of the river covered by the plume, 267 t of dust would have been deposited over the 16 km^2 of main channel floodplain immediately downwind of the clay pan. This rate of dust recycling to the river is, however, a significant underestimate of real inputs as deposition would have been enhanced by the filtering of suspended dust by the dense stands of trees growing in the channels within the main channel floodplain.

3 Regional and local-scale interactions: the Murray-Darling Basin

a Fluvial systems and dune systems: The Murray-Darling Basin occupies 1.06 million km^2 (Crabb, 1997) and rainfall varies from over 600 mm yr^{-1} in the east to around 250 mm yr^{-1} in the arid west. The Murray-Darling Basin has less extensive dunefields than the more arid Lake Eyre Basin (Figure 5). The reasons for this may lie in the different fluvial geomorphic and climatic settings of the two basins. The Murray-Darling system is internally draining (rather than an internal drainage basin), therefore although there are significant alluvial sediment inputs via deposition in the western (arid) sector of the basin, this may be a less prolific supplier of floodplain sediment than in the internal Lake Eyre Basin. In climatic terms, the two basins also differ. The floodplain sections of the Murray-Darling Basin occupy rainfall zones of >250 mm, whereas the main floodplain sections of the Channel Country rivers in the Lake Eyre Basin are in the <250 mm rainfall zone. Therefore, we would expect that the floodplain alluvium of the Lake Eyre Basin would be a more significant aeolian sediment source than the Murray-Darling Basin alluvium.

The main area of dunes in the Murray-Darling Basin is in the semi-arid to temperate Mallee dunefield. The southwest of the dunefield comprises sub-parabolic dune chains and low linear dunes (Lawrence, 1980). The north and eastern areas are characterized by short, low linear dunes (Wasson *et al.*, 1988) and source-bordering dunes including lunettes (Bowler and Magee, 1978). The large extent and associated range of environmental conditions in the Murray-Darling Basin suggests that dune development occurred as a function of the spatial environmental transition present in the catchment and that coupling of the fluvial–aeolian–lacustrine systems played a particularly important role in the formation of local source-bordering dunes. Based on stratigraphic and chronological evidence, Williams *et al.* (1991) suggested that the formation of channel source-bordering dunes in the region took place from 5.5 ka to 0.6 ka ago, when heavier winter rainfall initiated sufficient flow to carry a significant sandy bedload downstream. Summer conditions were very hot, dry and windy and this sand was deflated from the channel, forming dunes which were then reworked by rainsplash, runoff and wind. The channel source-bordering dunes only form when seasonal conditions enable this close-coupling of the fluvial and aeolian systems. Earlier in the Holocene lower wind speeds, a more even distribution of rainfall throughout the year reducing the amount of bedload transport and/or a more dense bank vegetation prevented the formation of source-bordering dunes (Williams *et al.*, 1991). Under current conditions, the dunes are not active owing to a well-developed vegetation cover and lack of sediment supply (Williams *et al.*, 1991) and can be described as discoupled from the fluvial system. The temporal sequence of sediment production (during humid phases), increased availability and transport (during dry summers) and reduced availability (during wetter conditions) accords with Kocurek's (1998) model of climate/sediment budget relations.

b Fluvial systems and dust transport systems: Figure 6 shows a zone of moderate dust storm activity extending from the Channel Country in western Queensland south onto the floodplains of the Murray-Darling Basin in western New South Wales, northwest Victoria and South Australia. The dust storm frequencies averaged for the floodplain sections of the Murray-Darling Basin (36 dust storms, 1960–2000), are considerably lower than for the Channel Country (71 dust storms, 1960–2000). Part of the reason for this results from differences in the rainfall ranges in the Murray-Darling (250–400 mm) and Channel Country (180–300 mm) floodplains (Figure 3). The dust storm frequencies of the most arid sector of the Murray-Darling Basin are higher (47 dust storms for 1960–2000), but this is still significantly lower than the Channel Country. The fluvial geomorphic and climatic evidence presented earlier to explain the less extensive dunefields in the Murray-Darling system applies equally to these differences in dust storm activity.

The areas of high dust emission are closely coupled to the floodplains but it is also possible that some dust can be recycled back to the river by dust deposition. Furthermore, if the dust transport direction is up-catchment, there is potential for sediment recycling on a regional scale similar to that described in the Lake Eyre Basin. Leys and McTainsh (1999) examined dust and nutrient deposition onto the Namoi River, near Gunnedah, New South Wales in the upper catchment of the Murray-Darling Basin. They measured deposition of 68 ± 15 t km^{-2} yr^{-1} for 1996–1997. This deposition rate is a composite of locally entrained dusts (being in a sub-humid rainfall zone these would derive mainly from unsealed roads and cultivation) and long-distance dusts travelling along the southeast dust path (Figure 5).

Over a longer timescale, evidence from loess deposits (Hesse and McTainsh, in press) suggests that large-scale sediment recycling occurred between aeolian and fluvial systems within the Murray-Darling Basin during the Last Glacial Maximum. Coupling of the aeolian and fluvial systems and the sediment cycling process is illustrated in Figure 8. High rainfall intensities lead to soil erosion by runoff in the upper river system and transportation from the more humid to the more arid parts of the basin via the internally draining rivers. These rivers transport the sediment and deposit it on floodplains in the west. Many of the Murray-Darling rivers flow in a southwesterly direction across the path of dust-entraining winds leaving extensive tracts of alluvium exposed to these winds. After desiccation, the alluvial fines are entrained by wind and transported east towards the river headwaters. A proportion of the dusts are re-deposited onto the catchments from which they originated and, of these, some directly re-enter the river system whilst a proportion of the dusts deposited are stabilized by vegetation and incorporated into soils to start the cycle again (Figure 9).

At a smaller scale, Fried (1993) suggests that changes from nonsinuous to sinuous channel forms on the Murray and Murrumbidgee floodplains during the Quaternary cannot be explained by catchment changes alone. He proposes that large inputs of aeolian clays and silts during the Last Glacial Maximum led to the development of sinuous channels by increasing suspended loads in rivers. Aggregation of these fines in saline waters then enhanced over-bank deposition, leading to greater river bank cohesiveness and stability, which in turn resulted in more sinuous channel forms (Fried, 1993).

4 Aeolian–fluvial response to Quaternary climate changes

A rapidly expanding body of evidence suggests that soils over large areas of the upper Murray-Darling Basin have received significant dust inputs. These soils are variously called: parna (Butler, 1956), dust mantles (Gatehouse, 2002) and loess (Hesse and McTainsh, in press). There is more limited evidence of Lake Eyre Basin dust contributions to the soils of southern Queensland (Hubble and Isbell, 1958) and northern New South Wales (Cattle *et al.*, 2001). This spatial distribution does not reflect the contemporary pattern of dust activity in Australia and suggests that dust emissions and deposition patterns may have been different in the past. Evidence suggests that the two

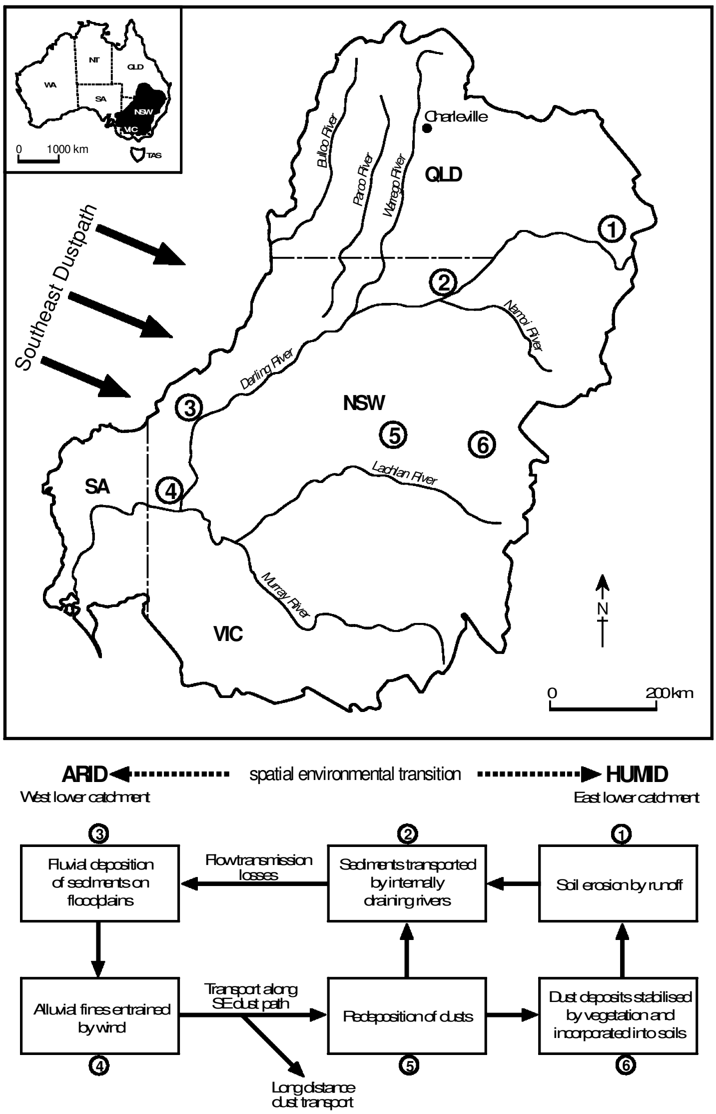

Figure 9 Murray-Darling Basin sediment cycle

basins we have used as examples responded very differently to the climate changes of the Quaternary. In particular, during the Last Glacial Maximum the Murray-Darling Basin appears to have been a more important dust source region than the Lake Eyre Basin, and this can be attributed to heightened aeolian–fluvial interaction in the Murray-Darling Basin.

McTainsh and Lynch (1996) made quantitative estimates of the effects of Last Glacial Maximum aridity upon dust storm occurrence in eastern Australia using selected climate change scenarios in their 'Et Index' climate model of wind erosion. They concluded that Last Glacial Maximum dust storm activity in the Lake Eyre and Murray-Darling Basins increased by similar amounts – 57% in northeast Australia (including the Queensland sector of the Lake Eyre Basin) and 52% in southeast Australia (including all except the South Australian sector of the Murray-Darling Basin). The authors, however, noted that these increases are likely to be underestimates, as their climate model 'did not take into account supplies of sediment to wind erosion' (McTainsh and Lynch, 1996: 270).

Quaternary environmental changes are likely to have had different effects on the two basins. First, as the Murray-Darling Basin is more humid than the Lake Eyre Basin, a decrease in rainfall during the Last Glacial Maximum would have exposed large areas of the lower floodplains of the Murray-Darling Basin to arid conditions (Williams, 1994) (Figure 10). In contrast the Channel Country floodplains are arid under present interglacial conditions. Secondly, the Murray-Darling Basin encompasses a larger rainfall range and has a higher total fluvial discharge than the Lake Eyre Basin. Consequently, the headwaters of the Murray-Darling river systems would still have received significant rainfall, maintaining sediment inputs to the lower floodplains whilst flood events and subsequent deposits would be greatly reduced in the Lake Eyre Basin. These two factors would have enhanced aeolian activity to a greater extent in the Murray-Darling than the Lake Eyre Basin because of the impact on sediment supply.

Field evidence of aeolian saltation deposits confirms that the lower Murray-Darling Basin did experience significantly enhanced aeolian activity during the Last Glacial Maximum, whereas such evidence is less apparent in the Lake Eyre Basin. There are much more extensive areas of low relief relic dunefields and coversands in the Murray-Darling Basin than is indicated by the dunefield map (Figure 5). Large areas of western New South Wales (approximately half of the state) are aeolian sand plain and this extends into southwest Queensland. The sand plains are not currently actively forming but were active during the Last Glacial Maximum (Williams, 1994). Evidence for greater aeolian activity in the Murray-Darling Basin is also available from studies of Tasman Sea sediments (Hesse, 1994), to which the deposition of dusts derived from southeast Australia has contributed significantly. According to Hesse and McTainsh (in press) dust deposition rates were three to seven times higher during the Last Glacial Maximum than in the Holocene. Furthermore Hesse and McTainsh, and Ikehara *et al*. (2000) state that the greatest dust deposition was south of 30°S, which is in the latitudinal range of the Murray-Darling Basin. The weight of evidence is therefore strongly in favour of the Murray-Darling being the major dust source region during the Last Glacial Maximum.

VII Future research directions

This paper provides a brief summary of the geomorphological implications of aeolian–fluvial interactions at a range of spatial and temporal scales. Much of the research that we have reviewed demonstrates that these two process systems are often

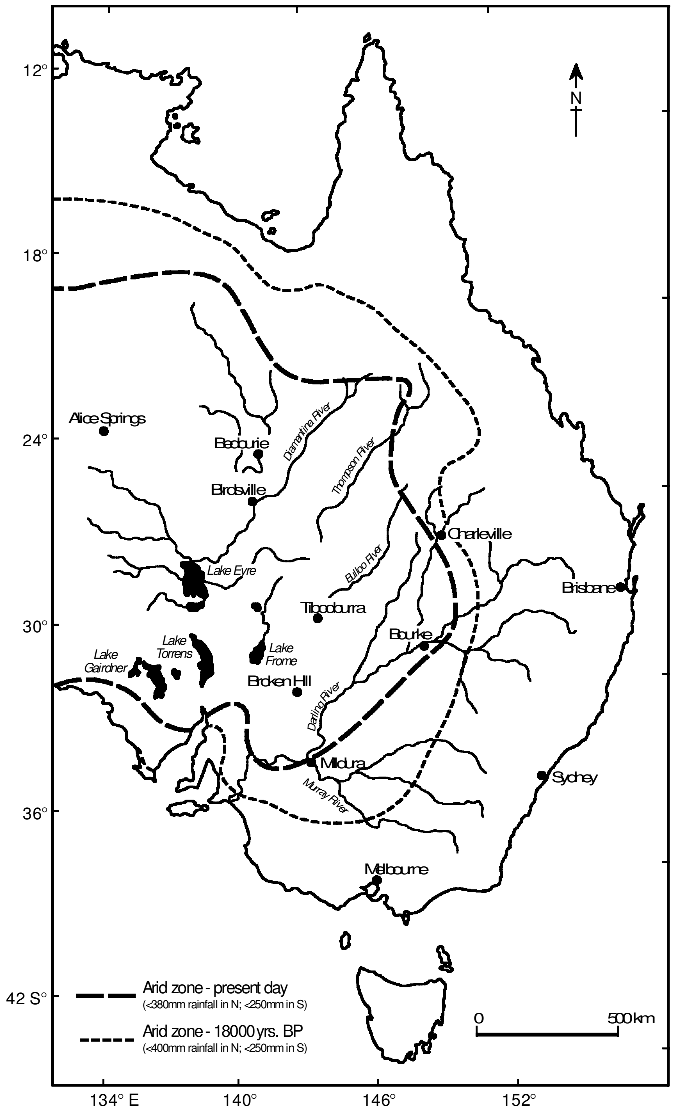

Figure 10 Possible arid zone expansion in Lake Eyre and Murray-Darling Basins during last glacial maximum
Source: after Williams (1994). Reprinted from *Quaternary Science Reviews*, Vol. 8, McTainsh, G.H., 'Quaternary aeolian dust processes and sediments in the Australia region', pp. 235–52. © 1989, with permission from Elsevier

closely related, or coupled by sediment transfer processes. The extended discussion of aeolian–fluvial interactions in Australia illustrates that interactions between the two systems are not only the result of temporal environmental change but can also be closely dependent on spatial transitions. The range of environmental conditions occurring in extensive catchments can promote interactions between aeolian and fluvial processes, and may be particularly important for large-scale sediment recycling between the two systems.

One critical factor affecting the interaction of processes is the role of floodplains, especially as suppliers of sediment to the aeolian system. To improve our understanding of how these geomorphic elements are coupled, further consideration of the factors which control the interface between the fluvial channel and the floodplain, i.e., factors which control how much sediment is deposited on the floodplain and associated landforms, is necessary. Recent research in the fluvial field has placed increased importance on the sedimentary relationships between channels and floodplains (Brierley, 1996; Woolfe *et al*., 2000) and, in drylands, this needs to be extended to include aeolian sediment systems.

In the Introduction to this paper, we noted that aeolian–fluvial interactions have been widely documented in stratigraphic sequences. Although we have highlighted many contemporary examples of aeolian–fluvial interaction, many existing 'modern analogue' studies are descriptive and lack contemporary process data (Bullard and Livingstone, 2002). In addition to this, closely coupled systems, particularly those where temporal shifts from aeolian to fluvial activity are very rapid (e.g., seasonal), may leave a more simple stratigraphic record than is suggested by the complexity of contemporary processes and environments (Brunsden and Thornes, 1979). For example, writing about interactions between aeolian, fluvial and lacustrine systems, Williams *et al*. (1991) noted that:

> Material is easily transported from one system to another so that it becomes reworked within another system. As a result of this continuous sorting of sediments, there is often no distinct lithology which is diagnostic of one particular system (Williams *et al*., 1991: 275).

Interpreting complex stratigraphic sequences and challenging apparently simple stratigraphic records in areas where aeolian and fluvial processes interact will require a far better understanding of contemporary relationships between the two systems than we currently have.

Finally, although we did not focus on temporal environmental changes, it is apparent that the response of aeolian–fluvial interactions at the changeover from one stable climate state to another is in need of further investigation. Rohdenburg (1970), for example, suggests that periods of geomorphic activity alternate with periods of stability but that these are not necessarily correlated with periods of different total annual precipitation. He argues that most geomorphic activity will take place during the changeover from one type of climate to another. Although there are some studies which support this, for example, transitions between century or longer duration warm and cold periods may be characterized by abrupt fluctuations in alkaline dust concentrations over periods of up to 10 years (Taylor *et al*., 1993a), it is an area that warrants further research.

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