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An evaluation of the role of physical models in exploring form–process feedbacks in alluvial fans

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Abstract Alluvial fans represent small-scale coupled transport/depositional systems that provide the opportunity to undertake detailed studies of non-equilibrium landform behaviour. Previous interpretation of fans in the field has tended to emphasise the importance of external controls on their evolution (e.g. climate and tectonics). However, recent theoretical models have shown that internal process-driven feedbacks may be equally important. Using a physical model, image analysis reveals temporal and spatial patterns in flow patterns over the building and fully-developed fan surface, both in the presence and absence of external forcing (change in water–sediment ratios). The pattern observed from the physical model is compared to patterns observed in both numerical model simulations and field fans in the Avoca Valley and Poerua in the Southern Alps, New Zealand. These comparisons led to a preliminary evaluation of the role of physical models in exploring form–process feedbacks in alluvial fans.

Key words alluvial fan; scaling; physical model; numerical model; field; New Zealand

INTRODUCTION

Alluvial fans represent small-scale coupled transport/depositional systems that provide the opportunity to undertake detailed studies of non-equilibrium landform behaviour. Previous interpretation of alluvial fans in the field has tended to emphasize the importance of external forcing on their evolution, focusing on the relative roles of tectonic setting, climatic influence and base-level change as controls on fan development (Hooke & Dorn, 1992; Ritter *et al.*, 1995; Whipple & Trayler, 1996; Harvey, 2002, 2005; Hartley *et al.*, 2005). Despite this, there remains an incomplete understanding of controls on alluvial fan evolution due, in part, to the limited amount of research conducted to date examining the influence of autogenic processes on fan morphology and its development. In particular, little attention has been given to the relationship between flow and sediment transport processes and how these may alter in response to changes in fan morphology. Numerical modelling has shown that autogenic mechanisms can drive complex responses to external forcing and promote cycles of fan aggradation and incision over a range of time scales (e.g. Humphrey & Heller, 1995; Coulthard *et al.*, 2002; Nicholas & Quine, 2007a,b). However, such models incorporate simple representations of fan processes that necessarily neglect much of the complexity apparent in the natural environment. Assessing the validity of such models requires an improved understanding of fan behaviour and processes derived from either field or experimental studies.

PHYSICAL MODELLING

Physical models have been successfully used in studies of alluvial fans by numerous researchers (e.g. Hooke, 1968; Schumm *et al.*, 1987; Zarn & Davies, 1994; Bryant *et al.*, 1995; Whipple *et al.*, 1998; Cazanacli *et al.*, 2002; Davies & Korup, 2007), and have been shown to reflect the processes that occur on natural alluvial fans, providing valuable information on various aspects of alluvial fan morphology and dynamics that would not have been possible to measure otherwise. Here, we present results from an experimental study of alluvial fan evolution that aims to provide new insight into the internal dynamics of flow and sediment transport processes on fans.

PHYSICAL MODEL DESIGN

An analogue physical model was used to observe the processes that occur on the surface of an alluvial fan as it evolves. This means that the model is not scaled to a specific prototype in reality, but instead is based on Hooke's (1968) "similarity of processes and performance" theory. The basic requirements for these physical models are that a number of gross scaling relationships be met, that the model reproduces some morphological characteristic of the prototype, and that the processes that produced this characteristic in the experiment can logically be assumed to have the same affect on the prototype (Hooke & Rohrer, 1979). However, certain initial and boundary conditions were considered. The scope of the model was restricted to represent only fluvial-formed gravel alluvial fans in a temperate environment. In addition, certain scaling relations were imposed to ensure realistic representations of model input conditions compared with those in natural alluvial fans. Several test experiments were conducted to ensure the suitability of these conditions. Using the environmental criteria outlined previously, three field sites were identified in the Southern Alps of New Zealand. Scaling laws, based on those by Yalin (1971), were then used to determine values for the model sediment feed rate and water discharge, and the model grain size. These scale relations, although approximate, served to strengthen the applicability of the experimental physical model to suitable fans in nature, in order to allow the results to be interpreted and applied more effectively. The grain size distribution used in the model included sizes that varied from 0.25 to 0.71 mm. The size distribution used here was restricted to sand sizes at the lower end, rather than including silt or clay that would be required to represent finer (sand) sizes present in natural fans. This fine cohesive sediment is a poor scale model of the larger non-cohesive sediment that it is meant to represent.

The experimental work for this project was carried out at the University of Exeter Sediment Research Facility, UK, in a custom built alluvial fan simulation basin. This consisted of a 3-m square plot with controlled sediment and water supply fed through an inlet channel to the fan apex (see Fig. 1). A variable speed gravity-fed sediment hopper supplies the sediment at a pre-defined rate to the inlet channel where it mixes with the water, being fed at a specified discharge from a regulated pressure tank, before reaching the entrance to the plot. The fan area is enclosed on two sides by clear Perspex walls, 0.7 m high, with an opening at the apex where the inlet channel is positioned, restricting the angle of the apex to 90 degrees. The surface of the plot is constructed from concrete; this material was used as it is impermeable. A semi-circular drainage channel was constructed at the lower end of the basin to allow free movement of water and sediment leaving the fan area. This drainage channel represents a boundary condition in the model, equivalent to a body of flowing water cutting across the fan toe, therefore preventing sediment build-up in this area and imposing a maximum extent on fan length. Sediment was manually removed from the channel throughout the experiment to prevent sediment accumulation and keep the channel clear.

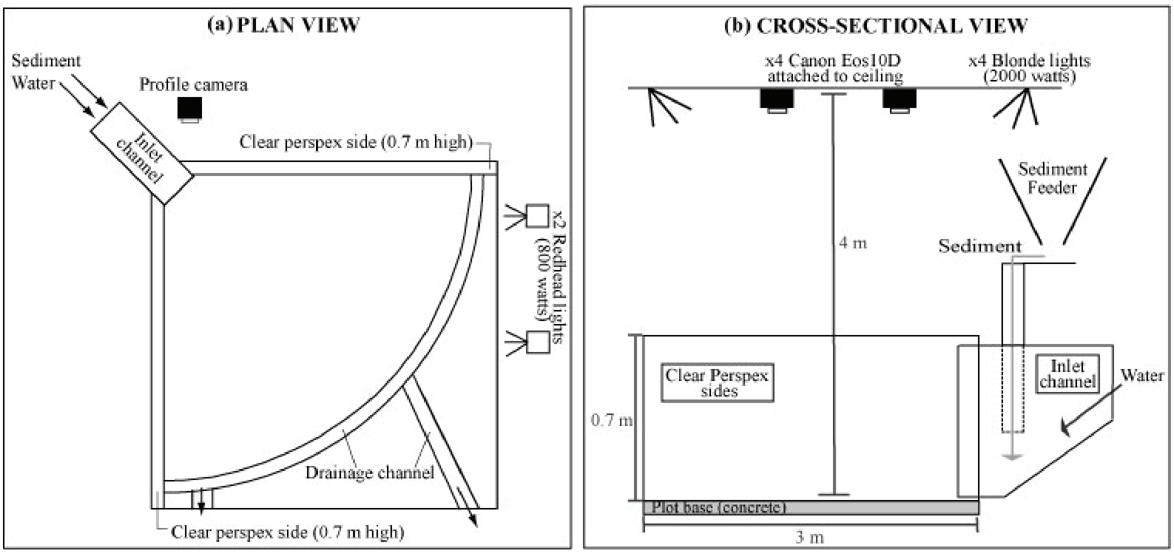

Fig. 1 (a) Plan view and (b) cross-sectional view (taken from position of profile camera on the plan view) of the experimental plot.

For all the experiments the inlet channel slope was set to 30 degrees, the plot surface had no slope, and the fan was allowed to form freely once the sediment and water were switched on. Four experimental scenarios are examined here (see Table 1). With the first three scenarios, at the start of each experiment the sediment and water discharge rates were set to the predetermined values and held constant throughout the experiment. The sediment and water discharges for Scenario 1 were determined from the scale calculations discussed above and through testing in trial experimental runs. The ratio of sediment feed to water discharge used in Scenario 1 was also used in Scenarios 2 and 3; however, absolute values of water and sediment feed rates were doubled for each respective run. Each of the experiments was run until an equilibrium profile was achieved, to enable a comparable end point between the three scenarios, and then continued until the sediment was exhausted to observe the processes that occurred once an equilibrium profile had been achieved. Scenario 4 maintained a constant water discharge rate but the sediment discharge was alternated between two values every 30 minutes (see Table 1).

Table 1 Details of the experimental scenarios considered here.

Scenario	Q (L s^{-1})	Qs (g s^{-1})	Duration (min)	Final fan slope
1	0.1	25	795	0.12
2	0.2	50	705	0.10
3	0.4	100	300	0.07
4	0.2	25/50	600	0.06

Q: water discharge rate; Qs: sediment discharge rate.

The results of these experiments were recorded by near-continuous photography with specialist stage lighting used to ensure a bright, even light source. A combination of overhead digital SLR cameras taking photographs of the plot surface at a high resolution every minute, and cameras recording the changing height of the apex through the experiment, were employed. This was supplemented by an overhead digital video recorder providing a continual qualitative record of changes in the fan. The variety of digital media provides a wealth of information on each of the experiments.

PHYSICAL MODEL FINDINGS

Constant ratio experiments

The experimental fans from Scenarios 1–3 all evolved following similar stages of fan development. Each experiment was characterised by progradation of a fan from the basin apex to the drainage channel that limits fan extent. Consequently, fan area and volume increased throughout experiments before reaching an upper limit. Fan volume increased linearly through time while the rate of increase of fan area declined nonlinearly through time. The spatial and temporal patterns of fan building observed on the experimental fans was complex with the number of channels, the channel geometry and fan morphology adjusting continuously whilst the fan prograded across the experimental basin. Channels formed on all parts of the fan throughout the course of the experiments. Consistent with the results of Schumm *et al.* (1987) and Whipple *et al.* (1998), it was found that the deepest flows occurred at the fan apex. The fans typically developed in four main stages, although the time spent in each stage varied between experiments, similar to those observed by Bryant *et al.* (1995):

- Sheetflow dominated the early stages of the experiment. Typically, over 50% of the fan surface was covered with water and no clear channels were present. Sediment deposition was prevalent, leading to rapid fan growth.
- As the fan continued to grow the flow alternated between sheetflow and the formation of unstable channels and braided sections. Sediment deposition was caused mainly through the

formation and abandonment of channels across the fan surface and in the depositional periods of sheetflow.

- Formation of one to two main channels; these migrated continually over the fan surface with channel avulsion and abandonment common. Areal distribution of sediment occurred incrementally with avulsions, lateral migration of the channels and channel abandonment.
- A single channel formed that was solely responsible for the sediment distribution. This channel became entrenched at the apex, often associated with terrace formation in the upper fan, and continued to avulse and migrate in the mid- and lower-fan regions, but this movement declined as the experiment progressed to its latter stages. Sediment deposition was limited to the toe area but the majority of the sediment was now transported out of the fan system.

The main characteristic of this sequence of fan development is a tendency for flow configuration on the fan to change from sheetflow dominated to predominately channelised as the fan grows. The time taken for this to occur lengthened with increasing sediment and water discharge rates (i.e. Scenario 3 had prolonged periods of sheetflow and took the longest to begin to channelise). In the absence of changes in fan input conditions or fan gradient over the course of these experiments, the tendency toward increased flow channelisation is hypothesized to be a product of the decline in fan aggradation rate through time. This slow-down in aggradation is a product of both the increase in area over which sediment is deposited as the fan progrades and, ultimately, the limit on sediment accommodation space that is imposed by the drainage channel at the toe of the fan.

Fluctuating sediment experiment

The observations from the fluctuating sediment scenario varied from those with a constant ratio as the fan was not allowed to grow and develop in the same manner. The general tendencies observed were that in the periods when the sediment supply was increased, sheetflow processes dominated and aggradation occurred, conversely, when the sediment supply was reduced channelisation and incision controlled flow on the fan surface. The sediment feed rates were alternated every 30 minutes and the process response to this change in sediment supply was rapid, with an almost instantaneous change from sheetflow to channelisation, or *vice versa*. Hooke & Rohrer (1979) and Schumm *et al.* (1987) on their episodic fluvial fan, and Zarn & Davies (1994), all proposed that radial fan slope altered with a change in the sediment–water discharge ratio, with slope decreasing with a reduction in the sediment–water ratio. For the fluctuating sediment experiment, the lowest sediment–water ratio relates to the periods of reduced sediment supply. And as can be seen from Table 2, the fan slope did vary between the different sediment supply states, with the lowest slopes associated with the periods of reduced sediment supply; i.e. in agreement with the other studies.

Although the general tendency throughout the experiment was for sheetflow and aggradation during the stages of increased sediment supply, and channelisation and incision during reduced sediment supply, the characteristics of these altered as the experiment progressed. In the initial stages of the experiment, when the sediment supply rate was reduced, the flow quickly changed from sheetflow to a wide channel along one flank; it remained in this location for a short time

Table 2 Fan slopes from the last four cycles of the fluctuating sediment experiment.

Run time (mins)	Fan slope	Sediment supply rate
360–390	0.064	Increased
390–420	0.063	Decreased
420–450	0.066	Increased
450–480	0.065	Decreased
480–510	0.066	Increased
510–540	0.065	Decreased
540–570	0.066	Increased
570–600	0.063	Decreased

before avulsing into a central position. Whilst in the periods of increased sediment supply the fan aggraded at a quicker rate with an increasing number of sediment supply cycles, thus raising the height of the fan apex from its previous highest point with each subsequent sediment supply increase. Towards the later stages of the experiment, after several phases of changing sediment supply, there was again a change observed. Once the sediment supply was reduced, a single incising channel formed towards the centre of the fan, this was occasionally followed by a brief period of instability when branch channels formed, but this soon stabilised and there was minimal migration of the channel from this position. When the sediment was increased again following this stage, the sheetflow was not as concentrated as in the early stages of the experiment, and aggradation at the fanhead was not as rapid. An equilibrium state seems to have been reached, with the height of the apex alternating between similar values between the incision and aggradation cycles.

In addition to the fluctuating sediment experiment, the sediment supply rate was reduced at the end stages of each of the constant ratio experiments to observe what impact this had. Once the sediment supply rate was decreased the incision at the fan head rapidly increased, and a prolonged reduction led to the formation of terraces in the upper fan area (see Fig. 2).

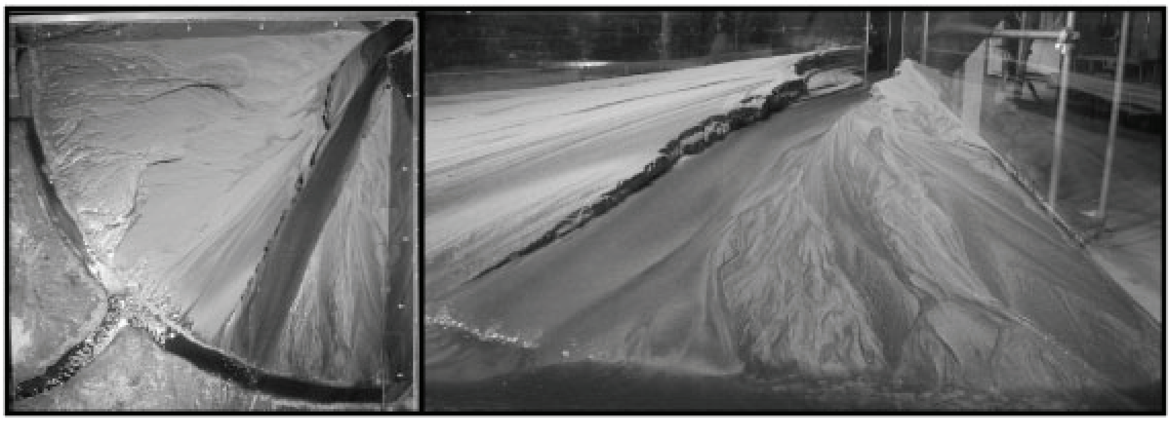

Fig. 2 Terrace formation at the fanhead following a reduction in the sediment supply rate – Scenario 2 after 670 minutes of run time with a 75% reduction in the sediment supply rate.

NUMERICAL MODELLING

Nicholas & Quine (2007a,b) presented a quasi-two-dimensional model of alluvial fan evolution that integrates sheetflow, channelized flow and transition stages into one model and calculates flow width as a function of the aggradation/degradation rate, i.e. degradation is when the flow is channelised (see Nicholas & Quine, 2007b, for a detailed explanation of the model). This model was developed in collaboration with the physical model presented and therefore, similar to the boundary conditions imposed by the physical model, assumes that the fan length and base level are fixed by the presence of a large river system at the fan toe.

Nicholas & Quine (2007a,b) found that the sequence of fan formation from the numerical model simulations followed phases similar to those found from the physical model observations outlined earlier in the paper. Fan building was characterized by progradation of the fan in a series of pulses. Initially, the fan aggraded and the fan was sheetflow dominated, the channel networks then braided and individual channels moved across the fan surface both by lateral migration and avulsion. Once the fan reached its maximum extent, the flow was channelised and fanhead trenching initiated (Nicholas & Quine, 2007a). Similar to the physical model findings, the numerical model simulations found that fan growth leads to a slow down in aggradation rate with time.

Nicholas & Quine (2007b) ran two different simulations over an 18 000-year period; the final fan geometry of each of these is shown in Fig. 3. The first of these examined fan evolution under conditions of constant environmental forcings and found that dramatic and persistent fan entrenchment (Fig. 3(a)) was a product of autogenic feedbacks between flow width, sediment transport and rate of aggradation (Nicholas & Quine, 2007b). They also conducted model runs in which the water discharge rates were kept constant but the sediment supply was perturbed by pulses of varying magnitude and duration. These transient variations in water and sediment supply are responsible for the formation of complex terrace sequences in the entrenched channel (Fig. 3(b)), similar to the physical model results (see Fig. 2). These simulations suggest that there is persistent fan entrenchment in the absence of external forcings, driven by positive autogenic feedbacks between flow width, sediment transport and the rate of fan aggradation. As with the physical modelling, the entrenchment is initiated where accommodation space limits continued fan growth, i.e. when the fan reaches its maximum extent.

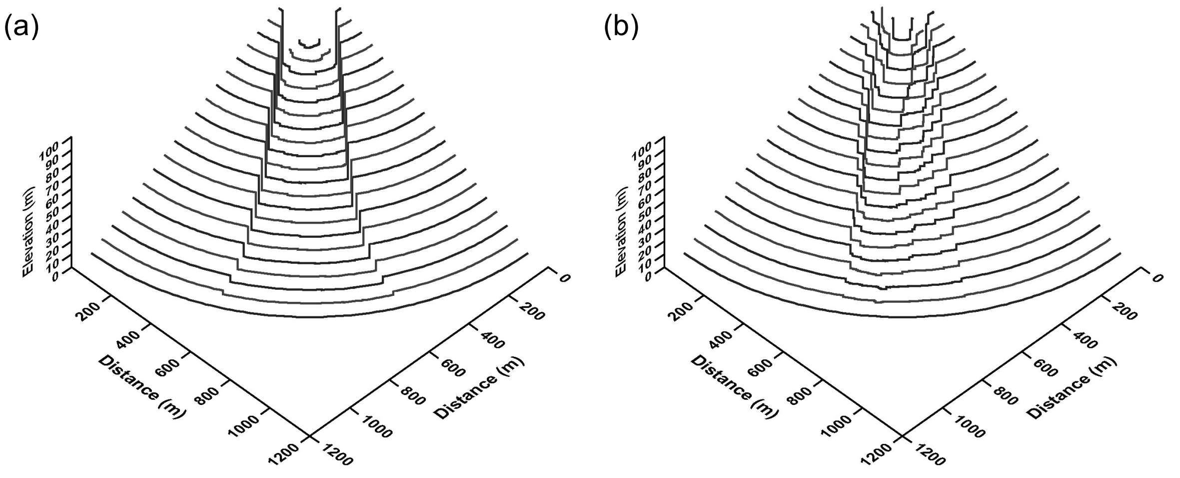

Fig. 3 Fan geometry at the end of two 18 000-year simulations: (a) sediment and water discharge rates are held constant over the duration of the simulation, (b) water discharge rate constant, sediment discharge rates are perturbed by pulses of varying magnitude and duration (taken from: Nicholas & Quine, 2007b).

TIME SERIES AERIAL PHOTOGRAPHY OF FANS IN THE FIELD

It is important to compare the results from physical and numerical model simulations with the field to ensure that the findings produced are realistic. Alluvial fans situated in the Southern Alps of New Zealand meet the environmental criteria imposed by the physical model and provide a suitable field test for these results. Two alluvial fans sites have been chosen, a tributary fan in the Avoca Valley, Canterbury (eastern side of the Southern Alps) and the Poerua alluvial fan, Westland (western side of the Southern Alps).

Long-term fan evolution: Avoca Valley, Canterbury, New Zealand

The Avoca Valley is a tributary of the Wilberforce River, which feeds into the Rakaia River; this area forms part of a larger study examining Holocene landform evolution. Centre Creek fan (see Fig. 4) is typical of many of the tributary fans in the valley; the late Quaternary upper fan surface is now inset by a series of Holocene terraces and the active channel gradient is approximately half that of the extensive highest surface (Nicholas & Quine, 2007a). The conventional interpretation of the situation is that it reflects a reduction in sediment supply over the Holocene and is a paraglacial phenomenon (Ballantyne, 2002). The physical and numerical models have both shown that entrenchment of the fan surface can be initiated through purely autogenic processes. However, the formation of terraces on Centre Creek supports the view that there was some reduction in sediment supply. Visually comparing the photographs of Centre Creek fan (Fig. 4) and Fig. 2, the end of a

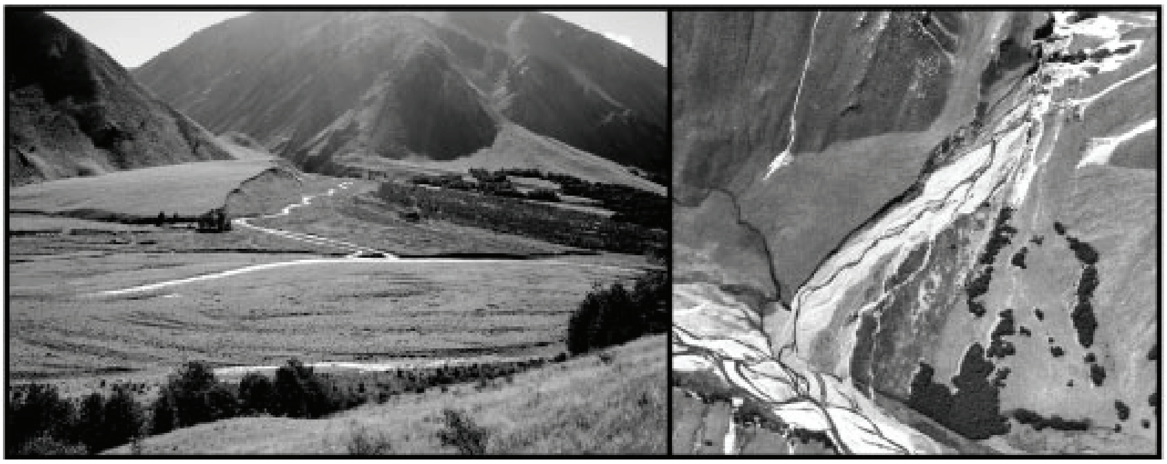

Fig. 4 Centre Creek, a tributary fan in the Avoca Valley, showing the incised active channel and terraces on the fan surface. Aerial photography courtesy of NZ Aerial Mapping.

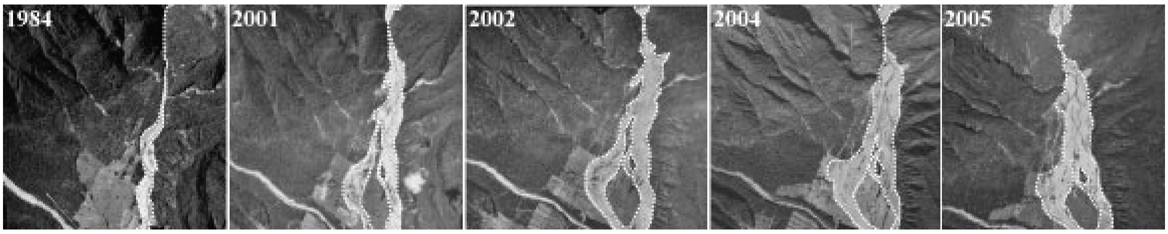

Fig. 5 Time series aerial photography of upper Poerua alluvial fan (dashed white line outlines active channel area) – 1984 shows the incised channel on pre-landslide Poerua fan and 2005 once the peak of aggradation had passed. Images courtesy of NZ Aerial Mapping (1984) & GeoSmart (2001, 2002, 2004 and 2005).

physical model run following a reduction in sediment supply, it can be seen that the images are very similar, suggesting that the physical model could well be simulating the processes occurring on the fans in the Avoca Valley. Quantitative analysis of this is currently being investigated.

Short-term fan changes: Poerua alluvial fan, Westland, New Zealand

In October 1999, a large rock avalanche fell from Mount Adams upstream of the Poerua alluvial fan, this formed a dam (80–100 m high) in the gorge below. After two days, the lake that had formed behind the dam overtopped and created an outburst flood, resulting in the deposition of a considerable amount of sediment on the alluvial fan (see Hancox *et al.*, 2005, for a detailed explanation of this event). Using field evidence and a physical model of the Poerua, Davies & Korup (2007) determined that following the landslide the fan switched from being incised at the fanhead to aggradation, with the peak of this aggradation having passed the fan apex by 2005 (see Fig. 5, showing time-series aerial photographs of the upper Poerua fan from 1984, pre-landslide, to 2005, when the major phase of aggradation had passed). Their physical model findings indicated that the input of sediment led to a steepening at the fanhead and infilling of the incised channel; following this, the stream began to rework the fanhead material downstream. If a second sediment input was then introduced, the fanhead would again aggrade, but more rapidly and to a higher elevation than previously. These results compare well with the findings from the fluctuating sediment experiment presented earlier in the paper, indicating that at this preliminary stage the physical model relates well to the field environment. Both suggest that sediment inputs will lead to aggradation, and that a second phase of sediment inundation will lead to higher apex elevation. However, it was found that with the fluctuating sediment experiment this effect declined with repeated sediment inputs.

CONCLUSION

By conducting experiments in a basin with fixed length and constant base level, the results from the physical model provide insight into the influence of temporal changes in aggradation rate on flow configuration in alluvial fans. They demonstrate that declining aggradation rate, driven by increasing fan area and an upper limit on sediment accommodation space, promotes temporal changes in flow configuration over the course of experiments. This transition takes the form of a change from sheetflow dominated conditions at the start of experiments to channelised flow as fan aggradation ceases. These effects were apparent to varying degrees in all three constant ratio experiments reported here, and are consistent with the concepts that underpin the numerical model of Nicholas & Quine (2007a,b).

The preliminary findings of the physical model of alluvial fan evolution presented here do appear to reflect the processes that have been observed on natural alluvial fans and in other experimental work. The results also appear to be comparable with the simulations from the Nicholas & Quine (2007a,b) numerical model and aerial photography and field observation of specific alluvial fans in the Southern Alps of New Zealand. The analysis is currently limited to purely qualitative similarities, and the extent to which the physical model results scale quantitatively with the field sites and numerical model output will be the next stage of investigation.

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