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Principles of sustainable development on fans

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Abstract

Rural development in New Zealand is currently expanding rapidly, and there is strong demand for sites for both residential and commercial occupation. Alluvial fans have always been attractive sites for development – they are well-drained, elevated above flood plain level and have interesting landscapes; however the need to understand fan evolution and recognise the hazards to development from future fan evolution is poorly acknowledged. Fans are low, semi-cone-shaped deposits that form where sediment carried by streams leaves steep, narrow mountain valleys and accumulates on broader, flatter basins, valleys or coastal plains. They are aggradational features, whose growth may however be limited by erosion of the fan toe by river or coastal processes. Unless all or part of the fan has become geomorphically inactive, it will in the future be affected by further erosion or deposition from floods or debris flows, which will be dangerous if development has occurred. Different types of fan present different hazards to development. Realistic hazard assessment and mitigation are essential if fan development is to be sustainable. Since fans are sediment-storage areas, any alteration of a fan stream channel to manage floods must also consider the natural sediment movement regime in order to allow sustainable developments. This frequently requires artificial sediment removal in perpetuity, which should be costed into the economics of a proposed development. Fan areas prone to debris flows are particularly dangerous due to the large volume, speed, destructive potential, rarity and unpredictable behaviour of debris flows. The debris flows that helped to form a fan may not have occurred in living memory or in the historical record, yet they can obliterate an existing landscape with a frequency relevant to the intended use. Sustainable development on fans requires sustainable management of bedload sediment transported by the river, which in turn requires either accepting the natural bedload transport regime and siting developments where they cannot be affected by river behaviour; or artificial removal and disposal of excess sediment for the lifespan of the proposed development.

Keywords

Alluvial fans, debris-flow fans, hazards, river management, land-use planning, aggradation.

Introduction

As in many other parts of the world, infrastructure development in New Zealand is at present increasing rapidly with expansion of land-based, tourism and recreation industries, and with peoples' increasing wishes and abilities to build residences and commercial premises (for example tourist facilities) in beautiful and secluded locations. Many new developments are deliberately sited in spectacular landscapes of outstanding beauty that are the result of active earth-surface processes. The desire for good views and to be out of reach of the obvious hazards on coasts or on major river floodplains leads many to favour the gently sloping, well-drained sites often found where minor streams leave steep hilly country and flow onto flat land. These sites are the depositional fans of the minor streams; they are active components of the landscape where sediment is deposited and removed from time to time by the action of the stream, usually when in flood.

While it is evident that local-government decision-makers who consider applications to develop land need to be aware of the hazards associated with such sites, this is often not the case. We have also found that the hazards to developments on fans are not always understood in New Zealand by the engineers, hydrologists and other consultants who, when requested, advise local government on the suitability of development sites. The May 2005 disaster at Matata, Bay of Plenty, New Zealand (McSaveney *et al.*, 2005) is a classic example of development permitted on land that showed geomorphic evidence of past debris flows, and for which there was even a history of such events. That this is also the case in other countries is demonstrated by the increasingly frequent reports of erosion, flash-flood and debris-flow disasters in rainstorms, almost all of which involve erosional or depositional episodes on alluvial or debris-flow fans. The 1999 disaster in coastal Venezuela (Wieczoreck *et al.*, 2000) is a striking example.

We thus recognise a need to summarise and explain the origins and nature of the hazards on various types of fan, and to explore the possibilities for sustainable (i.e., relatively safe in the long term) development in such locations. Although much of our experience is from the very dynamic landscapes of New Zealand, the geomorphic principles we describe are universal; however the frequency of occurrence of the phenomena associated with fan hazards is lower in less hydrologically and tectonically active regions such as Europe and Great Britain. This is fortunate, because opportunities to mitigate hazards by avoidance are fewer in lands like these with greater population densities. Other countries (e.g., Japan, Taiwan) have both active landscapes and high population densities, with little option but to attempt to constrain the natural processes.

In what follows, we first describe fans from a geomorphic perspective, and outline their functions as components of an active landscape – in other words, why they are there and what role they play in ongoing landscape evolution. This is contrasted with the assumptions implicit in society's use of them for development. We then look briefly at the various fan types and their behaviour; how they form and alter their form, and how they respond to natural and artificial changes in their circumstances. This leads to consideration of the conflict between the natural behaviour of fans and society's actions based on expectations of fan behaviour, which is the fundamental cause of fan hazards. We emphasise the points made by briefly recounting case histories of fan development and hazard mitigation in New Zealand, before discussing the options for mitigation of fan hazards that may allow sustainable development on fans.

Fans as landscape components

Fans are low-gradient, cone-shaped sediment deposits that accumulate where the transporting power of a stream becomes inadequate to carry its entire sediment load any farther downstream, so that the coarser fraction of the sediment is deposited on the streambed. This generally occurs where a river or stream ceases to be confined in a steep, narrow valley and is free to spread out to a greater width on flatter land. The combination of greater width (and hence lower depth) and lower slope reduces the ability of the water to continue transporting the sediment it has carried through the narrower, steeper valley upstream. So sediment is deposited locally, causing an increase in the elevation of the river bed (or 'aggradation'). This causes the river to overflow its banks at high flows, and to 'avulse' to a different course on the lower adjacent ground; it thus moves to and fro across the available width, depositing sediment and building up the typical low-angle fan surface as it does so (Fig. 1). This process has been extensively studied in small-scale laboratory models (e.g., Zarn and Davies, 1994) and is well understood.

The conditions generally required for fan growth include a steep, narrow valley system; significant coarse sediment supplied to and carried through the system, implying significant bedrock erosion upstream and relatively steep valley gradients to allow the coarse sediment to be transported; sufficient water flow at times to transport the coarse sediment as bedload; and an abrupt transition in the river's course from a steep, narrow valley to a wider, flatter area. These requirements are often met, for example, where mountains are uplifting along range-front faults, giving the abrupt topographic transition required, with orographic rainfall, frequent tectonic activity and concomitant landsliding. Such conditions are found in much of New Zealand, sited as it is on an active tectonic plate boundary in the strong westerly wind belt known as the 'Roaring Forties'.

In general, fan-surface activity depends on the delivery of sediment to the fan from upstream. Consequently, fan hazards result from processes involving sediment motion rather than simply from water flows. A fan may experience a major rain-generated flood flow without any troublesome increase in the river level or change in its position if no sediment is readily available for transport. If, however, there is a major sediment input in the catchment, even a moderate storm

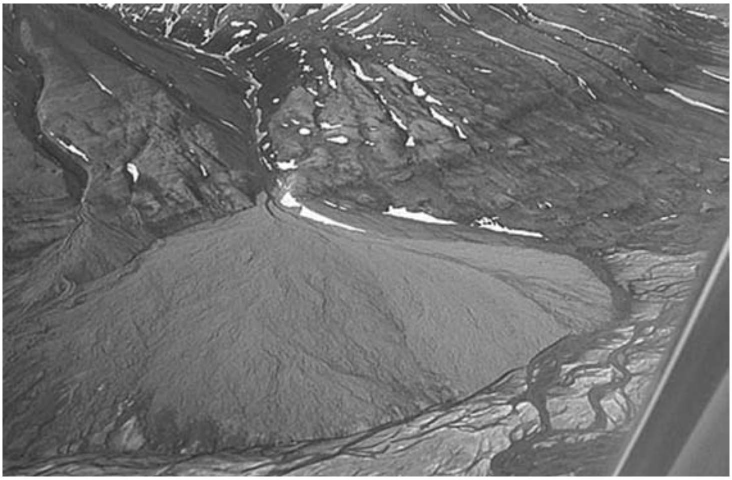

Figure. 1 – This alluvial fan is in Svalbard, Norway. Its toe is trimmed by the valley river flowing from right to left. A recent mid-fan to distal aggradation episode on the true left of the fan has prograded the fan toe, which is being intermittently eroded by the main river. http://www.mtholyoke.edu/proj/svalbard/photo/rawimages/originals_02/terrain2.jpg

and water flow rate can result in the river aggrading, and avulsing to a different flow path on the fan – a hazard to any facility in that path.

Fans are created by the river or stream flowing from time to time *at every location on the fan surface*; so, unless the fan surface can confidently be declared inactive – that is, the conditions that resulted in its construction can no longer occur – then every location on the fan surface will be the river bed at some time in the future. Thus *all active parts of a fan* are exposed to hazards from river flow processes from time to time.

Fans as development sites

By contrast, the occupation of fans for residential or commercial use assumes that the river will stay where it is and behave as it has in the past while development is present, or that it can be kept there by engineering. This assumption is not usually explicit, so when development is contemplated the corresponding questions are seldom asked. The time-frame involved in this assumption varies with the interest involved; for the developers, it is until they have completed the development (with a permit from the local Council) and received all payments due. For the purchasers of the developed properties, it is until they are resold or death (of the owners or their heirs), whichever comes sooner. For the responsible local authority it is the duration of its legal liability for the structural integrity of the buildings against damage by hazards – though this time-scale is very hard to define even when the return period of the 'allowable' destructive event is stipulated by building regulation (McSaveney *et al.*, 2005).

There is therefore a fundamental problem in 'permanent' human occupation of active fans; since every part of the fan will in the future be re-occupied by the river (unless the fan surface has become or been rendered geomorphically inactive), the human facilities will at some time in the future become part of the river bed (Fig. 2), unless, that is, the river can be controlled by artificially restricting its ability to change its course across the fan. Society's expectation of river engineering on fans is implicit in the rationale

Figure 2 – Awatariki stream debris-flow fan, Matata, Bay of Plenty, New Zealand, May 2005; here a new subdivision was in the process of development to its full potential (McSaveney *et al.*, 2005).

for fan development, and the reliability of river control on active fans is a vital question in sustainable development on fans. This is the issue that the present work seeks to explain and clarify, and to suggest strategies for resolving.

Requirements of current legislation

Under the standard codes associated with the Building Act (2004) it is appropriate to adopt standards of construction of dwellings such that they have a 90% chance of surviving their expected lifetime, usually taken as 50 years. It follows that the appropriate level of protection from destructive hazards such as debris flows or high-velocity flood flows is that of the hazard of 10% probability in 50 years (which is usually rounded to an event of 0.2% annual exceedence probability (aep) or 500-year return period). For protection from the inconvenience of non-structurally damaging hazards such as inundation by slow-moving water, a lower level of protection may be appropriate (such as the 2% aep commonly used in this context). There is no logical rationale for these particular, or any other probability choices; these arose after much debate as a consensus among the select group of engineers developing the standards, and represent an agreed compromise between safety and economy (A. King, GNS Science, Lower Hutt, New Zealand, *personal communication* 2007). They may be modified in future revisions, but there will never be a logical choice.

The allowable probability of hazard in the standards varies with the importance of the development. For example, buildings used by crowds rather than families are recommended to be not structurally damaged by events of 0.1% aep, while for buildings with post-disaster functions (fire stations, hospitals) the corresponding aep is 0.04% (AS/NZS 1170.0:2002).

The 0.2% and 0.1% aeps are recommended engineering practices, however flow records of rivers rarely extend longer than 100 years, and many smaller rivers and streams have no flow records at all. Debris flows can be the main threat to the integrity of structures on fans, however, understanding of debris-flow processes and debris-flow aeps is often meagre (Davies, 1997; Jakob and Hungr, 2005). We consider how the issues arising can be dealt with defensibly.

Geomorphic function of fans

Landscape behaviour

Here we consider the fundamental role of fans as *active sediment storage and transport regulators* in the overall behaviour of the landscape.

The erosion of the landscape is accomplished by gravity and water, often assisted episodically by heavy rain or by strong ground shaking in nearby large earthquakes. When slopes become steeper through uplift or basal incision, or are severely shaken, gravity-driven failures carry material from the slopes into the rivers. During heavy rain, slopes that are stable when dry can develop high pore-water pressures and collapse to the rivers below, even without ground shaking.

The sediment input from a catchment to a fan is determined by the rate of denudation, which is in turn determined by the slope, precipitation, ground-shaking intensity and geology of the catchment. Fan surfaces may or may not be in equilibrium; if they are not, then the quantity of sediment in storage in the fan changes with time, which means that the fan surface geometry changes. It is in the nature of geomorphic processes that these alterations occur episodically – that is, at infrequent intervals – so an active fan is likely to be an inconvenient place for human development at some time in the future. Fan-building episodes are unpredictable, and if the developer is lucky, the time before the next troublesome episode may be long. *The aim of the present work is to provide some guidance for ensuring that developments do not make the situation worse by demanding river-control measures that themselves increase the fan disequilibrium, and hence accelerate the next episode of channel avulsion or further, more costly control works.*

River behaviour

The function of a river is to carry to the sea the arbitrary quantity of sediment delivered to it per unit time *at the rate it is supplied*, using the arbitrary quantity of water per unit time available from precipitation (Davies and McSaveney, 2006). The way a river does this is to adjust its own slope and form by eroding and/or depositing sediment. It therefore follows that the (dynamic equilibrium) slope and form of a river are exactly those that allow the water available to carry the sediment to the sea at the rate it is supplied, on average over (undefined) long time periods. The river characteristics (slope, width, depth, course, channel pattern) are determined by seismicity, precipitation, slope angle and rock type – the last determining both the gradient at which slope failures occur, and the size distribution of the sediment carried by the river. Thus river character is a function of geology, slope angle, seismicity, volcanism and precipitation. Vegetation may also influence river character.

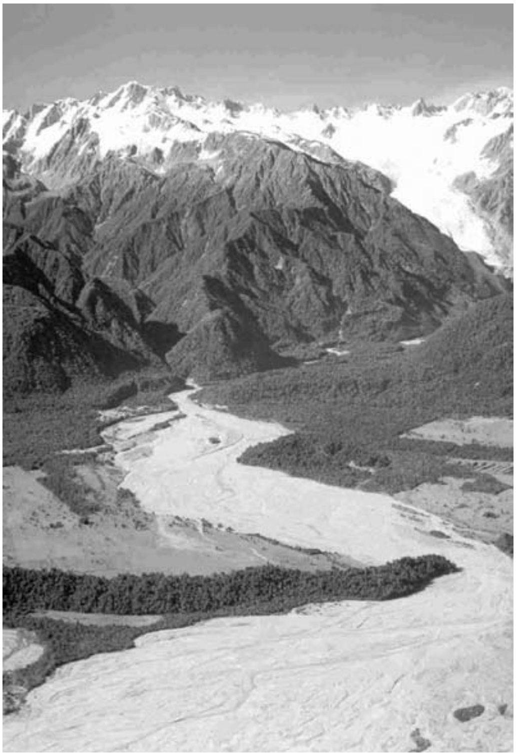

Figure 3 – A very dynamic landscape: Franz Josef, Westland, New Zealand, with the active fanhead of the Waiho River at the base of the Southern Alps.

Photo by Lloyd Homer

Every alteration, natural or artificial, in sediment or water supply rates is thus likely to cause a change in the character and behaviour of the river on the fan, leading to problems for developments that assume such changes do not occur. Similarly, any artificially imposed change in river character creates a conflict with the determining conditions by altering the sediment-transport capacity of the water, and disturbing the balance between sediment supply and transport rates, resulting in alteration of the both the quantity of sediment in storage and the sediment outflow. Since much human development occupies parts of the landscape – including the fans – comprising sediment in (temporary) storage, the result is, in principle, a change to the human-occupied landscape.

This framework utilises the fact that the transport capacity of a river is a positive (but variable) function of river slope. Thus if river sediment-transport capacity is locally less than supply rate, the excess sediment supplied accumulates. The local channel elevation, and therefore the channel slope both increase, as does the transport capacity (Fig. 4). Accumulating sediment also changes channel form, again in such a way that the sediment-transport capacity increases. This scenario can be tentatively generalised to landscapes as a whole; the form towards which an active

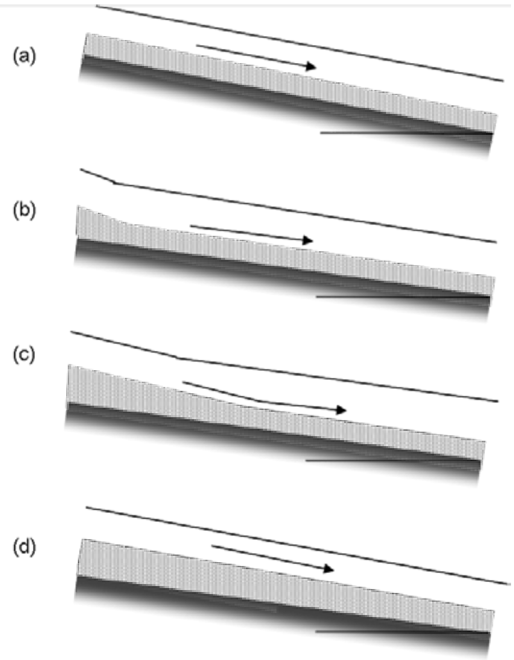

Figure 4 – Effect of artificially reducing the slope of a river channel.
(a) Original channel in equilibrium with water and sediment inputs.
(b) Slope reduced; sediment supply is greater than transport capacity so upstream sediment accumulation increases water surface slope.
(c) Sediment accumulation and slope steepening prograde downstream.

landscape is evolving is that which allows the rate at which sediment is supplied by erosion and denudation to match that of sediment transport across the landscape (mainly by rivers), in the long term.

Implications for fan behaviour

In this framework the behaviour of alluvial and other fans is that the fan evolves to adjust the ability of the river to move sediment across the fan reach at the rate of sediment supply from upstream. Changes in sediment- and/or water-supply rates cause the river to evolve to a different shape, thus changing the form of the fan. The life history of a fan is often complex in dynamic landscapes. Base-level lowering, caused for example by tectonic uplift or lake drainage, can cause headward river incision that leaves part of a fan surface isolated. Even then unusual events such as massive landslides can cause temporary aggradation that can re-activate the fan surface (Davies and Korup, 2007). Neither of these will be anticipated by anyone trying to understand the fan by considering only the *river part* of the landscape system. In active landscapes especially, it is difficult to rationalise the behaviour of any particular component without considering the way in which it is affected by the other components, at all time-scales.

The processes described above apply to several different processes of fan formation. For example, some fans are formed wholly or partly through the action of debris flows, which are an extreme form of high-concentration sediment transport that behave very differently from normal river flows; they contribute quite dramatically to the evolution of fans and therefore pose exceptional hazards (Jakob and Hungr, 2005). Landslides in catchments also have their own particular effects on fans (Davies *et al.*, 2005; Hancox *et al.*, 2005; Davies and Korup, 2007), which need to be recognised and understood in order that their contribution to hazards are appreciated.

Fan Types

Detailed scientific classification based on size, process, morphology, stratigraphy, time-variation, sediments, aridity of environment etc. is by no means straightforward (Schumm *et al.*, 1996); here we outline a pragmatic classification of fan types based on the different types of hazard they pose.

Alluvial fans

The term 'alluvial fan' is often used indiscriminately for any fan, irrespective of its genesis. Herein we restrict the term to

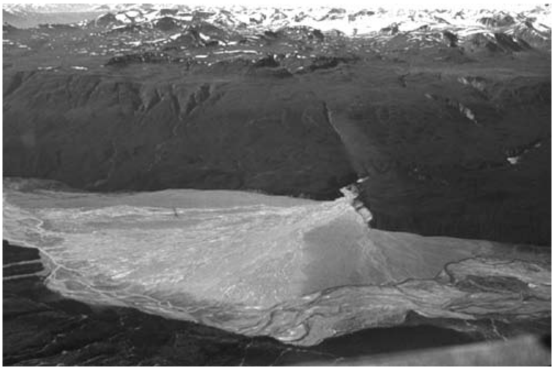

Figure 5 – Disappointment Creek fan, Yukon, Canada.

Photo by Philip Giles

those fans formed entirely by deposition of sediment by the river flow (Figs. 1, 5). Any fan wholly or partly formed by debris flows is specifically excluded from this section of our nomenclature and dealt with later, because of the different type and degree of hazard presented by debris flows.

Alluvial fans have been studied extensively in the field, the laboratory and computer simulations, so their behaviour is well known (e.g., Hooke, 1967, 1968a, b; Hooke and Rohrer, 1979; Schumm *et al.*, 1987; Zarn and Davies, 1994; Koss *et al.*, 1994; Bryant *et al.*, 1995; Parker *et al.*, 1998). Briefly, a fan forms by deposition from river flow in which aggradation causes lateral translation of the channel, building the fan as it extends laterally and longitudinally. Often it is found that there are smaller-scale internal consistencies in the fan development process (e.g, Zarn and Davies, 1994) that allow the immediate future behaviour of the river to be anticipated – at least in laboratory situations where water and sediment inputs can be held steady. Field situations are intrinsically more variable, because water and sediment inputs vary widely and quasi-independently, but experience seems to suggest that the consistent aspects of laboratory behaviour underlie the noise in field behaviour (Zarn and Davies, 1994).

Since alluvial fans can be large and of low slope (≤ 3°; Marchi *et al.*, 1993), large volumes of sediment need to be moved to alter their morphology, and they respond slowly to input changes because of the normally low bedload sediment concentration of the river flow (≤ 1000 ppm by weight). Fans that prograde onto a large flat surface can be permanently aggradational, since they can continue to build their toes outwards and increase their volumes. If the fan toe is able to be eroded even discontinuously by, for example, river or wave action, an *equilibrium fan* can develop that, although active, is neither aggradational nor degradational in the medium to long terms (but may be either in the short term). It is clearly important to ascertain whether a fan is close to equilibrium or not, to develop a true picture of its behaviour and hazards.

The morphology of an alluvial fan is typically smoother than other types (Figs.1, 5), because the depositional processes comprise shallow-water flows transporting coarse sediment as bedload, a process that does not give rise to large topographic relief.

Debris-flow fans

Debris flows (e.g., Jakob and Hungr, 2005) are a distinctive phenomenon of sediment transport, in which a very high concentration of fine sediment in a flow alters the flow dynamics so that large quantities of very coarse material can be transported. This results in the development of a succession of discrete surges or translation waves of material with the consistency of wet concrete moving down the stream channel, often with an accumulation of the largest sediments (boulders) at the front (Fig. 6). The waves move at many metres per second and can be some metres high, and there may be many at intervals ~ minutes in a single episode. Such events occur from time to time in many small, steep catchments (Wilford *et al.*,

2004) in shattered rock, but in any specific catchment debris flows have a frequency of occurrence of the order of a few times per century (e.g., McPhee, 1990), or less.

A debris-flow surge exiting a narrow valley onto a fan will widen and become shallow, and slow down dramatically; surges usually stop when the fan gradient decreases below 5 or so degrees (e.g., De Scally and Owens, 2004). A stopped surge in a fan channel can block it, so that a subsequent surge may be deflected to one side, onto a different part of the fan surface; thus *a debris flow can occupy any part or all of a fan*, even if the stream channel is somewhat incised into the fanhead (Fig. 7). Avulsion is normal for debris flows on a fan, unless a single flow can occupy all of the fan. Debris-flow fans are composed of the deposits of debris-flow surges, and their surface morphologies reflect the lobate shape of surges. This generally contrasts with the smooth appearance of alluvial fans, and is a valuable geomorphic indicator; any fan with a lobate appearance is formed – at least partly – by debris flow surges (Fig. 8).

Apart from the difference in processes, debris flows affect human infrastructure much more severely than do water floods. Rapidly-moving surges with large bouldery fronts cause severe damage to structures in their path. The nature of debris flows, particularly their low frequency on a given fan, their ability to avulse rapidly to any part of a fan, and their great destructive potential, make them a very severe hazard to development anywhere they can occur on a fan.

Mixed fans

Pure debris-flow fans are rare, because of the infrequency of debris flows in a given catchment. It is overwhelmingly likely that between debris flows, streamflow reworks debris-flow deposits, giving the

Figure 6 – A large debris flow, Yunnan, China. The flow front is about 2 m high and travelling at about 5 m/sec. This surge has a density of about 2 tonnes/m^3, and lacks coarse material at the front because little is available in the catchment.

Figure 7 – Debris-flow fan with incised channel, Buller, New Zealand. A new dwelling is on the fan surface to the right, just out of the picture.

Figure 8 – Lobate debris-flow fan surface, Death Valley, USA. (http://faculty.gg.uwyo.edu/heller/Sed%20Strat%20Class/Sedstrat3/sedlect3%20gifs/debrisflow%20fan2.jpg)

fan a partly-lobate, partly-smooth (or even wholly smooth) appearance. Often the lobate form appears only in the upper part of the fan (the fanhead), because that is where debris flows occur most frequently. If a long time elapses after the occurrence of a debris flow, all evidence of lobate forms on the fan surface may be eliminated by alluvial reworking – though anomalously large clasts may be present in the stream channel or on (or beneath) the fan surface. Hence absence of surficial evidence of debris flows is not necessarily evidence of their absence, and in principle any fan with gradients steeper than about 3° should be treated as a potential debris-flow fan (Marchi *et al.*, 1993) warranting detailed investigation.

Identifying catchments that can generate debris flows is clearly important. Recent work on debris-flow catchment and fan characteristics allows this to be done within a GIS (e.g., Rowbotham *et al.*, 2005) and preliminary trials (Welsh, 2008*)* indicate that such methods are extremely useful to indicate potential debris-flow sites. Site investigation is necessary to confirm such indications by geomorphic evidence; however evidence can be obscured or obliterated by subsequent fluvial or anthropogenic activity.

Episodic-aggradation fans

Some fanheads in active mountain terrain are markedly steeper than the fan surface downstream, with the river incised into the fanhead by several metres, and the depth of incision decreasing to zero some distance downstream. Conventionally such situations were considered to result from long-term decrease in catchment sediment yield. However we have found (Davies *et al.*, 2005; Davies and Korup, 2007) that such morphologies can also arise through very large but infrequent sediment inputs, such as result from severe earthquakes causing many small landslides, or from large landslides that form major sediment sources. A river can erode the landslide material and transport it downstream to the fanhead, where the higher sediment concentration causes a steeper fan surface to develop. Normally the surface of an episodic-aggradation fanhead is well above flood level, and the river flows in an incised channel at the lower gradient of the fan downstream. Only following further very large (but rare) sediment inputs is the river able to aggrade sufficiently to avulse over, and again increase the elevation of, the fanhead. When the excess sediment in the river has been worked through the system the river returns to its normal gradient and can re-incise into the fanhead (Davies *et al.*, 2005; Davies and Korup, 2007).

As well as anomalously steep gradients, episodic-aggradation fanheads can also have series of buried soils in their stratigraphy. This is because there is time between fanhead aggradation episodes for soils to form on the surface before being shallowly buried by the next aggradation episode. Aggradation episodes can be so aggressive that existing soil is stripped off by the flow, and buried soils are found more consistently at the lower-

Figure 9 – A dwelling sited on a small fan below a steep, vegetated gully in moraine, Westland, New Zealand. The vegetation on the fan surface is younger than that on the surrounding hillslopes, probably indicating relatively recent erosive activity.

energy edges of the fanhead. A further useful distinguishing characteristic of an episodic-aggradation incised fanhead is that its surface soils are indistinguishable in age from those of the active fan surface downstream; by contrast, if an incised fanhead is inactive in the longer term, its surface soils will be of greater age than those downstream.

It is important to identify episodic-aggradation fans if development is proposed, because their steep, incised fanheads may not be immune from sediment deposition over longer timescales of habitation.

Dynamic equilibrium fans

If the volume of sediment making up a fan is constant over time, then the flow of water across the fan surface is able to transport sediment across and away from the fan at the rate it is supplied at the fanhead. This means that in the long term the fan morphology is steady. Such a situation usually is caused by the toe of the fan being episodically eroded (by wave or river erosion) at the same rate that the sediment flux is episodically trying to prograde it; such a situation is evident in Figure 1.

Equilibrium fan surfaces may still be subject to river avulsion, because short-term excess sediment inputs can still cause local, temporary aggradation and therefore avulsion. The whole fan surface therefore can be reworked by the river in the longer term, but without causing net erosion or deposition other than in the short term. However, the frequency of reworking and avulsion is likely to be lower than for a fan that is aggradational in the long-term – that is, one whose toe is still prograding (Ashworth *et al.*, 2004).

Response to environmental changes

All of the above fan types evolve over time, as various mixes of water and sediment are supplied to them from upstream. This causes variations in fan behaviour over a time scale of individual events to centuries, attributable to natural variations and feedbacks in the precipitation and erosion that supply water and sediment to the fan. Two natural situations can cause the overall morphology of a fan to alter, causing all or part of the fan to change from active to inactive or *vice versa*; these are change of base level (causing alteration in the rate of sediment supply and/or transport capacity), and change of climate (causing alteration in the rate of water supply, and possibly of the rate of sediment supply also). A third environmental change that can affect fan behaviour is human land use.

Base-level change

As mentioned in the introduction, fans often form in the vicinity of active faults, and they are therefore subject to the effects of further fault movement. In the case of strike-slip faulting, where the relative motion is lateral, the river course may develop an increasing offset, without affecting fan behaviour dramatically in the short term. If significant vertical offset occurs on the fault, however, the gradient of the river is affected, and this may have more significant consequences.

For example, if the mountain catchment of a fan river is raised upstream of the fanhead, the catchment base level is effectively lowered, and the fan is then at a lower level relative to the catchment. The catchment will respond to the effective increase in gradient by eroding faster, supplying sediment to the fan faster, and building a steeper fanhead in the same way as that caused by a large landslide sediment input. When the catchment has adjusted to the change, i.e., eroded so that its physiography relative to the fan is restored, then the river will incise into its steeper fanhead, leaving an area of fanhead that is no longer active; this may be completely eroded given sufficient time. Severe seismic activity will probably be associated with the tectonic uplift, which may cause landslides of a range of sizes (Malamud *et al.*, 2004) and a shorter-term increase of sediment input; this seismogenic input and its effects will generally be much more rapid, and therefore prominent than those due to tectonic uplift.

Faulting or folding across a fan, or at its toe, will have similar effects, but will also cause fan channel gradients to change, causing nick-point recession (upstream uplift) or ponding (downstream uplift), and their consequential effects on the river system. Alteration of base-level by rising or falling sea- or lake-levels will have corresponding effects, but without an accompanying seismically-driven increase of sediment input.

Climate change

Climate alteration can cause significant responses on fans. For example, advance of a glacier in a catchment can cause increase of sediment delivery to a fan as sediment previously stored on valley floor and sides is reworked and transported downstream by the subglacial drainage system, but valley storage between the glacier and the fanhead can attenuate this increase. Glaciations also affect sea level, causing associated base-level changes.

A marked increase in precipitation will clearly increase the ability of a river to transport sediment across a fan; however, it can also cause an increase in sediment delivery as hillslopes are more often saturated and unstable, and weathering increases, so the effect on the fan is not necessarily to reduce the fan gradient as might appear to be the case at first sight. More rain may allow more vegetation to flourish, altering the temporal distribution of sediment supply in the longer term. Further, in the long term, increased erosion of a mountain range reduces its elevation and therefore the load on the basement rocks, leading to increased uplift (Pinter, 1997). Thus increased precipitation does not necessarily lead to alteration of the gradient of the river. It will, however, lead to changes in river morphology and possibly avulsion frequency. Corresponding results are to be expected from reduction in precipitation. Changes in storminess have been suggested as the reason for changes in behaviour of rivers draining the Ruahine Ranges, Hawke's Bay, New Zealand (Grant, 1966). Any major change in the water and sediment inputs to a fan, including changes in precipitation style, variability or intensity, will alter the fan morphology, and can cause previously inactive areas to become active and *vice versa.*

Perhaps the most profound changes are to be expected from climatic variations that alter fan base level. Sea-level fall, for example, will cause a coastal fan to extend, and, depending on the gradient of the former sea bed relative to that of the fan surface, either aggradation or incision of the fan surface can occur. Sea-level rise, on the other hand, will not immediately alter the fan gradient, but may alter the erosion rate of the fan toe, changing the fan from equilibrium to non-equilibrium or *vice versa.*

Land use

Land use can significantly change river behaviour, by altering the sediment input rate and also the peak discharge of floods. However, land use generally affects only soil erosion, rather than bedrock erosion, and thus does not significantly alter the long-term (i.e., geological) erosion and sediment delivery rates. In addition, much regolith material is fine and is transported as suspended load by rivers, and does not alter the river morphology much (though it is important to remember that debris flows can be initiated by large inputs of fine sediment, usually from slope failures (Jakob and Hungr, 2005). Hence, since fans are sometimes so large that very large changes in volume are needed to cause major changes in morphology, changes in land use are likely to be less significant than tectonic or climatic changes in altering fan behaviour. In effect, even complete devegetation can only temporarily accelerate erosion (from storage) of already weathered rock (regolith); once this is gone the erosion rate is again controlled by uplift or weathering rate, and will reduce again.

Alteration of vegetation is likely to be more influential on sediment delivery rates in large, low-gradient catchments than in small, steep ones, but the former are associated with correspondingly large, low-gradient fans, which must respond slowly to even large changes in sediment input rate. Hence, although in some situations drastic alteration of land use (e.g., urbanisation; Williams, 1976) can cause correspondingly drastic alterations to river behaviour, land-use changes usually have short-term (~ decades) and moderate effects on the behaviour of large fans.

Earthquakes

Many fan catchments are located in areas likely to experience strong ground shaking in nearby large earthquakes. As a consequence of strong ground motions, we can expect larger-than-usual short-term sediment input to streams, and hence larger-than-usual sediment inputs to fanheads. Fanhead aggradation is more likely in the period following a major earthquake; and if such an event has not been experienced recently, or is not historically recorded, that aggradation may surprise and harm occupants of the fan. There may, however, be stratigraphic or vegetation evidence of prehistoric events of this type (Davies and Korup, 2007).

Earthquakes are particularly important where debris flows can occur in a fan catchment. The probability of heavy rain initiating a debris flow is strongly related to sediment availability, so a major storm following an earthquake that causes widespread rockfalls has a higher-than-usual probability of generating a debris flow. This must be taken into account in selecting a design magnitude for debris-flow protection structures such as bunds and debris basins, if the design event maximum annual probability is specified (presently 0.2% in New Zealand) and the probability of a major earthquake is significantly larger than this – as it presently is in the vicinity of the Alpine fault on the west coast of the South Island, New Zealand (Rhoades and Van Dissen, 2003; Yetton *et al.*, 1998). The post-seismic event magnitude then becomes the design magnitude.

Effect of fan behaviour on development

Fans respond to alterations in water and sediment inputs by aggradation or incision and river erosion or avulsion. Any development on a fan that is intended to be 'permanent' (i.e., has a long-term resale value) will be at risk of damage if the river can affect it.

Aggradation is the most troublesome aspect of fan behaviour, and since all fans are aggradational in origin it is the most common. Whereas an incising river reduces its ability to move laterally across a fan as it cuts deeper into the fan (because the deeper it gets the more sediment it has to move to shift a given distance sideways), an aggrading river finds it very easy to avulse rapidly across any part of a fan lower than its present level. Aggradation usually takes place episodically, following large sediment inputs into the river system; the latter are not predictable, so aggressive aggradation can take place, often during severe storms, with little warning. Being associated with severe storms and avulsions, the location of future aggradation episodes is also difficult – if not impossible – to predict. Aggradation is not only troublesome, it can be hazardous to human life. On sufficiently steep fans, the possibility of debris flows raises this hazard to a very high level, since these events can access all parts of a steep fan and are quite capable of destroying buildings, with little warning (Fig. 2).

Incision, by contrast, often occurs gradually. Although it may well be accompanied by lateral erosion of the river banks (because the river now is unlikely to braid and will probably meander widely instead), the location of this erosion is predictable even if the timing of the high flows that cause it is not. Thus, although incision can be troublesome, and may require developments to be relocated, it is often avoidable by sensible siting and is seldom hazardous to life. If debris flows can occur in a catchment with an incised fan, the possibility of the incised channel being filled by a debris-flow deposit, and subsequent surges accessing the fan surface, should be considered.

The natural behaviour of active, particularly non-incising, fans is inconvenient to the presence of long-term developments.

Managing fan behaviour means managing sediment

Now we examine the possibilities for artificially managing the behaviour of fans. First we consider what needs to be achieved for such management to be successful, and the practical implications of this achievement.

The objective of managing fan behaviour is to reduce potential damage to existing or planned developments to acceptable levels. Since damage or hazard is inevitable on all active parts of fans, it is necessary to render inactive (to some known degree) those active parts of fans where developments exist or are planned, and to ensure that lives are not endangered by either the rendering, or the effects of rendering, or the consequences of design being exceeded. If this can be achieved, risk to the developments will be reduced to acceptable levels. Occupants, the law and developers do not require risk to be reduced to zero, so an acceptable non-zero degree of risk must be chosen, which apparently widens the management possibilities. However, given

- the intrinsic imprecision in assessing the probabilities of occurrence of small samples of future events such as major sediment inputs and floods;
- the paucity of fan-behaviour data from which to construct such probabilities;
- the lack of understanding of risk in the general population that may be at risk; and
- the increasing desire expressed by society to reduce economic loss and premature human death to a very low level,

it is in fact doubtful if this alters the situation usefully.

The major requirement for reducing risk to developments on fans is to control the occurrence of aggradation and avulsion on the fan surface. Aggradation and avulsion are caused by large quantities of sediment being delivered to the fanhead, relative to the water being delivered at the time. Hence there is a need to 'manage' the sediment arriving on the fan in excess of that able to be maintained in transport across the fan by the river. This excess sediment may be present because of high rainfall causing bank or hillslope erosion, because of the river undercutting a hillslope, because of seismic shaking causing anything from a minor rockfall to a catastrophic mountainside collapse, or simply because a previously-input sediment volume has arrived at the fanhead after moving down the catchment for some distance and time. The timing and magnitude of the management measures required cannot be anticipated, and because the most likely time for aggradation to occur is during floods, an 'immediately on-demand' management system is hazardous and unrealistic. Whatever system is used, it must be able to *passively* manage very large volumes of sediment during floods. The effect of the management system must be to prevent sediment getting outside the controlled area.

In turn this requires that the active channel be restricted; all active parts of a fan are in fact the natural river bed, because at any time in the future any of it can be under flowing water. By thus restricting the active channel, we become *committed to keeping the river in a particular (usually its present) position on the fan – in perpetuity*.

Thus, in order to safeguard developments on active fans, we have to *render part of the fan inactive*. Since the inputs of water and sediment naturally generate an active fan, we have to *modify the river so that it will not deposit sediment in the developed area – i.e., it can transport the water and sediment inputs without lateral migration*.

At present, knowledge of river behaviour cannot explain what differences avulsion and lateral migration make to the ability of a river to transport sediment. Empirically and theoretically, we know that a moderate degree of inhibition of lateral movement lowers the bedload transport capacity of a river (Davies and McSaveney, 2001, 2006; Davies *et al*., 2003), so that we must expect that a river fixed in one location on a fan it has formed will steepen, because in the absence of lateral migration it can no longer transport the sediment supplied with the water available at the existing fan slope. Aggradation of the designated river bed becomes inevitable, and is the universal experience on active fans with controlled rivers.

Reduction of sediment supply from erosion in the catchment is also impractical in all but the short term. In Europe and Japan, series of 'check-dams' attempt to do this by storing sediment behind them and preventing river incision (and thus hillslope undercutting). Experience in the Varuna catchment, Switzerland in 1987, however, illustrates dramatically the temporary nature of such efforts (Davies and Hall, 1992). Construction of check-dams caused sediment delivery from the catchment to the fan to cease after about 1920, until in 1987 a moderate rainstorm caused the check-dam system to fail, and sufficient sediment was delivered in that one event to restore the sediment delivery rate to its long-term mean value. Sediment delivery is a geo-hydrological process caused by uplift, weathering and denudation; it cannot be halted permanently, and erosion-control techniques only change the magnitude-frequency relationship of the delivery events from small and frequent to large and infrequent. The latter are far more difficult to avoid in siting developments, and in the long (by human standards) intervals between them development is likely to occur on land vulnerable to damage by the next event, increasing its potential damage.

Implications for river management

It appears that, in general, the 'management' or 'control' of fans by alteration is not sustainable over any but very short timescales (Davies and McSaveney, 2006). The timescale on which this lack of sustainability becomes apparent varies with the rate of sediment supply to the river reach concerned. In 'old' landscapes such as those of Europe and UK, with low rates of uplift and sediment production, it may be centuries before the response of the river system to an imposed change becomes apparent (i.e., troublesome). It is significant that in the later years of the 20th century, European engineers began re-widening naturally braided rivers that had been artificially narrowed two centuries previously, because of increasing difficulty in maintaining stable beds. In the more dynamic landscape of New Zealand it seems to be typically twenty to fifty years after river control that troublesome aggradation becomes apparent. This is of course also a function of river size – small streams react more rapidly than large ones in general, because they have higher bedload sediment concentrations.

Management strategies for fans

From the above, the possibilities for permanent long-term modification of river behaviour on fans are limited. Where debris flows can occur, the problem is much more difficult – so much so as to be possibly insoluble (Davies, 1997), and the only reliable response to development proposals on debris-flow susceptible fans is to decline them.

Any structural modification of a stream on a fan carries with it the requirement to maintain the natural rate of sediment removal from the fan. The rate of sediment supply to the fan will not alter except by random coincidence. Since there are empirical and theoretical indications that artificial alteration of streams can often *reduce* their sediment transport capacity, artificial sediment removal from the altered stream becomes a requirement. This is a cost that should be considered in development and management decisions; it is a recurring cost for the life of the development. This strategy has been used successfully to date in protecting parts of the greater Los Angeles area from debris flows, by using debris basins that require emptying after every significant event (McPhee, 1990; Johnson *et al.*, 1990), and the same strategy is in use at Aoraki/Mt Cook, New Zealand (Skermer *et al.*, 2002). If appropriate provision is made for sediment removal, there seems no reason why artificial channel modification to protect developments on fans should not be successful in the long term, but the economic implications must be acknowledged at the outset.

In the case of an alluvial fan, the location of the sediment removal site could perhaps most effectively be at the fan toe. There are indications from laboratory models (Zarn and Davies, 1994) that lateral channel translation is usually initiated by aggradation at the fan toe, so if this is prevented the entire channel across the fan might be stabilised in normal flow and sediment input regimes. There always remains the risk of rapid sediment build-up anywhere on the fan in an extreme event, during which sediment removal will probably be impracticable, so warning and evacuation measures are still required to protect life; but the probability of such a situation occurring can be reduced by continual long-term sediment removal at an adequate rate.

This strategy addresses the primary cause of the failure of many past fan-management measures – failure to recognise the necessity to deal with sediment delivery to the fan. Landscapes change because sediment moves from place to place from time to time, and any artificial intervention in any natural water-sediment system must recognise, respect and allow this. Management measures that only deal with water are inadequate.

If long-term sediment removal is uneconomic, or undesirable, there is little prospect of altering the behaviour of a stream to allow sustainable development on an active fan. In this case the options are finding an alternative development site, which usually has political, legal and economic consequences; or accepting the risk of increasing hazard from stream behaviour, particularly in extreme events. In the latter case, effective flood warning and evacuation measures can reduce the danger to life, but not to fixed property.

A tragic example of the risks that attend structural ‘control’ of a mountain torrent is documented by Benito *et al.* (1998). The 1998 Biescas flood in the Central Pyrenees, Spain, killed 87 people in a camp site on an alluvial fan. The flood destroyed 31 out of a series of 36 dams and a canal built to protect a highway from flooding. The failed dams were the source of the sediment which caused the transformation of a rainstorm flood into a large debris flow which, on reaching the fanhead, avulsed from the normal stream channel to devastate the camp.

An important social consequence of altering a river – particularly if prominent control works are used – is that once the works are in place, the perception will be that the area previously at risk of flooding or aggradation is safe, so development is likely to proceed apace. When (not if – because it is never economic to attempt to control the maximum possible event) the works fail to control a super-design event, the costs will be very much greater than if the works had not been built. Whether the economic gain in the flood-free period offsets the additional losses when the works fail, and whether the losses and gains are suffered by the same people, is purely a matter of luck, depending on when the super-design event happens.

Case examples

Black Birch fan, Aoraki/Mt Cook

Black Birch fan is an alluvial fan in Mt Cook National Park (Whitehouse and McSaveney, 1990; Fig. 10). It is an active aggradational fan, prograding over the Hooker River flats and building up its surface accordingly over time. Until the late 1960s, no development occurred on the fan in spite of its proximity to Mt Cook village, the primary centre for the Park. In December 1957 a large storm caused massive sediment movements in several streams in the area, and a 1960 aerial photo shows the fan surface almost completely covered with freshly-deposited gravel, with the stream on the true left side of the fan.

During the late 1960s the stream moved to the opposite side of the fan, and in the 1970s, due to growing pressure for accommodation, dwellings were built on the true left side of the fan. At the time no consideration was apparently given to the natural behaviour of the fan; if it was, the conclusion must have been that the stream could, if necessary, be controlled. In an era in which huge power development schemes were being constructed nearby by moving whole rivers across the landscape, this attitude is perhaps understandable, but in the local sediment-supply context it was nevertheless mistaken.

By 1979 a considerable number of buildings existed on the true left of the fan. In December of that year a severe storm occurred, during which Black Birch stream aggraded about 6 m due to a minor landslide just above the fanhead, and threatened to avulse down the true left of its fan. The dwellings on the fan were evacuated, and only heroic work by a bulldozer-driver prevented large-scale destruction. Following this event a larger control bank was erected to keep the stream in its course on the true right of the fan. In this situation, the sediment carried by the stream has to deposit at the toe of the fan where the gradient reduces, and so aggradation proceeding upstream from the fan toe was geomorphically inevitable. By 1979 a further decision had already been taken – to site the village sewage treatment ponds on the true right side of the fan, close to the river, so that they could be neither seen nor smelt from the village. This required that the sewerage be piped across the width of the fan to the ponds – thus foreclosing the option of allowing the stream to flow directly down the fan, or of allowing it to occupy the true right half of the fan if it wished. From this time on the community was committed to maintaining the stream in its current position, come hell or high water; and, as further investigation showed (McSaveney and Davies, 1998), to removing accumulated sediment from the channel *in perpetuity* to maintain the safe flood-carrying ability of the river. Even with new stopbanks and a sediment removal policy in place, the risk remains of a large sediment input (as in 1979) overwhelming the banks during a major storm, and a warning-evacuation system is in place for this contingency. At Aoraki/Mt Cook the most likely devastating event is not a major flood: it is an Alpine fault earthquake (current probability ~ 1%

per annum). This will certainly cause large sediment input into the Black Birch stream catchment, and make maintenance of the river control works a matter of extreme doubt in subsequent storms.

In hindsight the initial development of the fan may in the future be seen as unwise. It set in train a sequence of events that has proved inescapable and extremely expensive, and considerable hazards still remain on the fan. Had the dwellings been sited in any of the many much less geomorphically-active locations available close to Mt Cook village, all this difficulty (and the inevitable future difficulties) would have been avoided. Had the longer-term consequences of developing an active aggradational landform been appreciated at the initial stage the story might have been much different.

Glencoe Stream, Aoraki/Mt Cook

The Hermitage Hotel at Mt Cook is one of New Zealand's iconic tourist destinations. It is sited on the depositional fan of Glencoe Stream (Fig. 10), a small, very steep stream that shows evidence of large debris flows in the recent past (McSaveney *et al.*, 1996). The nature of the stream and the hazard were not recognised until 1996. The degree of investment in the Hotel and other buildings was such that relocation was politically unacceptable, so protective walls (Skermer *et al.*, 2002; Fig. 11) were erected upstream of the hotel and around a debris basin, designed to deflect and trap the largest debris flow to be expected in a 200-year period. The rationale for selection of this unusual return period is unclear. In the absence of any even approximate data, arbitrary design parameters were unavoidable; the Hermitage is now safer than it was previously, but how much safer is unknown. What is particularly interesting is that, since the protection structures were built, the Hermitage has expanded dramatically, so that many more people are now at risk from super-design events. Since the risks are essentially unquantifiable, this situation cannot be demonstrated to be irrational; it is an interesting example of economically-driven decision-making in the absence of risk data. What is certain is that one day a debris flow will occur that is greater than the ability of the protection works to cope. That day could be very soon, which would be unlucky for present-day stakeholders, or it could be many hundreds of years hence, which would be

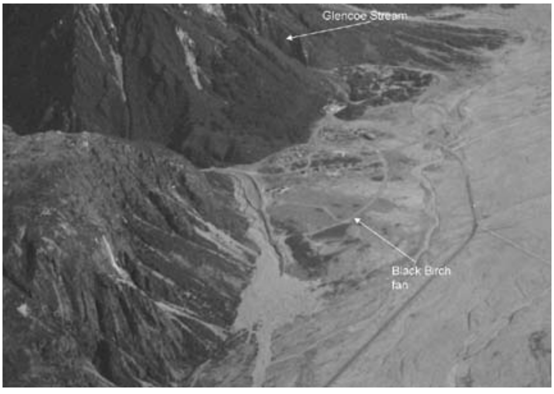

Figure 10 – Aoraki/Mt Cook village: Black Birch fan (lower) and Glencoe Fan (upper). The Hermitage is immediately below the tail of the upper aarrow.

Figure 11 – Debris-flow deflector wall (right) at Glencoe Stream, Aoraki/Mt Cook. Note debris-flow terrace (from 1957 event) on far side of stream. A larger, older terrace is hidden in the trees behind it.

lucky for them. When it happens, it will be a major disaster, but we cannot tell whether the costs will then be seen to outweigh the benefits of the years of occupancy prior to the disaster. The earthquake hazard is the same as for Black Birch fan.

Matata, Bay of Plenty.

In May 2005 the small town of Matata on the Bay of Plenty coast was devastated by debris flows from several of the streams that run through the settlement (McSaveney *et al.*, 2005; Figs. 2, 12). 20% of dwellings were damaged by the debris flows (Fig. 2), but there were no deaths or significant injuries. Subsequent investigation showed that the town is sited on the debris-flow fans of a number of streams; some houses had large boulders in their gardens that were impressive features of landscaping. There was memory of previous less intense events, and records of a number in the last century. The 2005 event was triggered by a very intense rainstorm which caused landsliding in many places nearby; the residents were unaware of the possibility of such an event and were unaware of what had hit their town.

A cursory inspection by anyone knowledgeable of debris flows would have identified the hazard if the question had been raised prior to the developments on the fans, but this did not occur. This is a remarkable lesson in the need to identify hazards prior to permitting developments on fans. It is not the fault of the responsible council, because their officers had not been educated about debris-flow fan characteristics. Discussion on mitigation measures continues at present (March 2008). A number of damaged houses have been removed, and will not be rebuilt until adequate mitigation measures have been taken; some will never be rebuilt.

Figure 12 – The Awatariki Stream after the May 2005 Matata debris flow. The damaged settlement can be seen between the hills and the coastal lagoon (McSaveney *et al.*, 2005).

Waiho River fan, Franz Josef Glacier

The Waiho River has a catchment of about 170 km^2 in the western Southern Alps just north of Mt Cook. High tectonic uplift rates, very steep slopes (Fig. 3) and plentiful precipitation (at least 14 000 mm a^{-1}; Henderson and Thompson, 1999) in the area result in rapid transfer of sediment to a number of alluvial fans at the western range-front of the Southern Alps. Some of these fans are limited in extent by marine erosion of their toes, so are equilibrium fans. Most of them have rivers incised some meters into the fanheads because past large sediment deliveries following landslides cause fanhead aggradation, into which the rivers incise once the excess sediment has been transferred to the sea. The last major earthquake in the area was in c. 1717, which may explain the general incision found in West Coast fanheads (Davies *et al.*, 2005; Davies and Korup, 2007).

The Waiho River was deeply incised into its fanhead at the beginning of the 20th century; since then, the need to protect the only State Highway through the West Coast from erosion and sediment deposition caused the river to be confined artificially to about 30% of its natural fanhead area. The response of the river (McSaveney and Davies, 1998; Davies and McSaveney, 2001; Rouse *et al.*, 2001;

Davies *et al.*, 2003) has been to aggrade and steepen until its bed is now about 15 m above its former level in the early 20th century. The management strategy to date has been to continue to raise the control banks, which encourages and allows the river to continue to aggrade; the river bed is now some metres above surrounding (developed) land and infrastructure, and the flood risk is becoming unacceptable. The long-term solution to this situation remains unclear; unless the river has now attained a gradient that allows it to move all the supplied sediment through the fanhead reach, further aggradation must be anticipated. Again, if the potential consequences had been realised before recent major developments alongside the river, much current and future difficulty might have been avoided – a Holiday Park has recently been relocated from a fanhead site, because of the particular risk of a landslide-dambreak flood at that location from the Callery tributary of the Waiho (Davies, 2002).

Discussion

Fan-hazard mitigation options

From the above it is clear that the conventional means of protecting fan developments from flood and sediment hazards (river control) are not reliable unless the natural sediment transfer rate of the fan can be maintained. Davies and McSaveney (2006) show this to be difficult unless the river can be narrowed very considerably, a measure unlikely to be successful on a steep fan with highly variable water and sediment inputs. If the natural sediment transfer rate cannot be maintained, the inevitable aggradation of the river bed must be contained; the only practicable way to do this is by artificial sediment removal, which is a continuing cost. It is also very difficult, if not impossible, to predict reliably when most of the sediment moves onto and across the fan during major floods.

An option worth contemplating, where development is not too intense, is to protect each building on the fan with its own diversion bank, the objective being to allow the river to move across the fan as and when it wants to, preventing it only from accessing the land area actually used for development. Roads and paths will be destroyed in floods, but if combined with a flood warning-evacuation system this option might allow reasonably secure investment on non-aggrading alluvial fans. This strategy cannot succeed where the development is too intense to allow the river sufficient room to function naturally.

Clearly this strategy is not suitable for debris flows. The Matata experience shows that an energetic debris flow can damage everything in its path. Davies (1997) showed that structural defences against debris flows are unavoidably unreliable, so exposing lives to debris flows is always unwise (the Hermitage experience notwithstanding). Similarly, warning/evacuation systems for debris flows (and in fact for any floods in small catchments) provide too little warning to be useful; it is perhaps better to be caught by a debris flow inside a house than outside trying to evacuate – one likely reason for the lack of casualties at Matata. There were probably no more than ten minutes between the initiation of the Matata debris flows and their arrival at the settlement. Evacuation triggered by forecasts of intense rain is in principle feasible (e.g., Davies and Hall, 1992), but the inevitability of (and in fact necessity for) false alarms may make the effectiveness of this strategy questionable. Developments in weather radar combined with very short-term forecasting will in the future reduce the frequency of false alarms.

Time frames

This discussion highlights one of the difficulties of reconciling human uses of active and energetic natural systems; the time-frame of immediate human concern is at most a generation or two, or the expected life of a building (say 50-100 years), whereas the time-frame required for the behaviour of a natural system to become fully apparent may be several centuries or even millennia. Hence we may not yet appreciate the hazard potential of many fans. On the other hand, extreme behaviour of the system can always occur in the immediate future. In the context of active fans, this means that human occupation is *always* unsafe to some extent – a fact that is rarely appreciated, and rarely communicated to those who need to be aware of it. So occupation of an active fan always requires that some degree of risk is accepted, and it must therefore be reduced to that degree or managed – presumably in a responsible society it cannot simply be ignored. It is perhaps to be expected that society appears to be becoming increasingly risk-averse; but it is notable that society is simultaneously becoming more inclined to take legal action when people or investments are damaged by natural hazards, perhaps indicating that hazard mitigation will in future become more litigious.

Conclusions

1. Hazards on fans are caused by large quantities of sediment rather than by large quantities of water, so their management requires knowledge of sediment processes.
2. To be sustainable, development on fans must be preceded by knowledgeable assessment of the geomorphic history and likely geomorphic future of the development site.
3. This requires that those responsible for land-use planning need to be sufficiently knowledgeable about fans and their behaviour to be able to recognise a fan and aware of the need to seek appropriate advice.
4. Appropriate knowledge is available in the scientific literature, and appropriate advice is available from professional geomorphologists.
5. Siting facilities on active parts of fans incurs risk of damage during the lifetime of the facility; assessment of the risk requires knowledge of the fan behaviour. Acceptable risk levels are prescribed by regulation.
6. Management of risks by engineering manipulation of the river or stream is likely to alter (generally increase) the natural activity of the fan, thus increasing the risks.
7. Continued sediment removal appears to be a requirement for sustainable river management on most fans.
8. Debris-flow fans are particularly dangerous as development sites. Debris flows are unpredictable and very destructive; past debris-flow activity can sometimes be identified by the characteristic morphologic signatures and by surface slopes > 3°.

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