Journal of Hydrology (NZ) 36(2): 127-145, 1997

Long-term management of facilities on an active alluvial fan – Waiho River fan, Westland, New Zealand

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Abstract

The proglacial Waiho River, Westland, New Zealand, and its tributary the Callery River, form a large alluvial fan, at the head of which is sited the township of Franz Josef Glacier. The very dynamic geology of the area, and its climate, cause the river and fan to be very active, and this results in the facilities of the township being threatened by aggradation and flooding from the Waiho River. In addition to rainstorm flooding, the fan is also susceptible to the potentially catastrophic results of glacier-burst and landslide dambreak flooding. Traditional methods of river control cannot provide an adequate degree of security for facilities, inhabitants and visitors.

An example of a long-term strategy is illustrated, by means of which such security could be achieved. It is based on knowledge of the evolution of alluvial fans; on acceptance of the fundamentally aggradational nature of the Waiho fan; and on acceptance that accurate prediction of detailed behaviour of the fan is unlikely to be available in the foreseeable future. It involves sequential redevelopment of key facilities, so that immediate serious hazards are avoided and the township can continue to service the tourism industry of the area in the long term.

Introduction

The Waiho River rises in the catchments of the Franz Josef glacier and the Callery River, northwest of the main divide of the Southern Alps, South Island, New Zealand. The Waiho emerges from the mountains at the head of an extensive alluvial fan; here lies the tourist township of Franz Josef Glacier. As well as being a centre for visitors to Westland National Park, the township also services the agricultural industry on the Waiho River flats. The West Coast highway (State Highway 6), the main (and only) traffic artery for the whole of the West Coast, crosses the Waiho at the township.

During the period of European settlement the behaviour of the Waiho has varied, ranging from deeply incised to presently aggrading. The recent aggradation of the Waiho River is threatening the township, stretches of SH 6, the road bridge, river control works, an airstrip, sewage ponds and a holiday park area at Franz Josef by increasing the height of flood peaks relative to the level of these facilities.

The present aggrading behaviour of the Waiho River at the head of its fan has caused serious problems for the road bridge and for the airstrip, and continuation of this aggradation will make continued use of other facilities problematic. The difficulties of maintaining locally- and nationally-valuable human resource use in a dynamic glaciofluvial environment are rapidly becoming apparent. To date little has been done other than remedial action for immediate problems as they arise, while the fundamental problems remain essentially unaddressed.

This report attempts to put the requirements for human use of the natural resources of the area in the context of scientific knowledge of the physical processes that have produced the features now used as resources. The continued action of these processes will inevitably conflict with the present usages, giving rise to hazards. The ability of science to reliably predict the future behaviour of the river system is assessed and found to be low; in this uncertain environment, management strategies must be developed to cope with the most extreme "normal" behaviour likely, and also with the occurrence of catastrophic events. These strategies must also be able to be implemented incrementally, as and when each stage becomes necessary. All plans will require serious consultation with concerned groups and individuals in order to be accepted and implemented.

Physical setting

The long mountain chain of the Southern Alps dominates the physiography and climate of Westland; it rises to 3754 m at Mt Cook, only 30 km from the coast. The mountains form a barrier to the prevailing moist westerly airflow of the "Roaring Forties", and mean annual precipitation exceeds 11,000 mm west of the main divide. Much of this precipitation falls as snow above about 1500 m, feeding the Franz Josef and Fox glaciers, which terminate as low as 300 m a.s.l. in the vicinity of rain forest – an unusual juxtaposition that has much to do with the status of the region as a World Heritage Area.

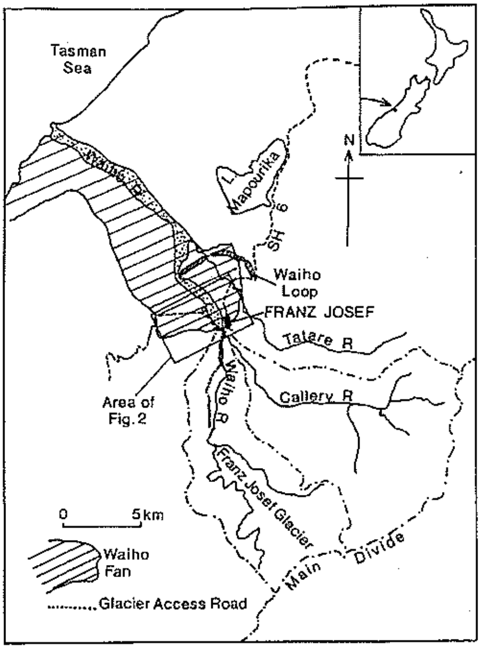

Figure 1 – Waiho River area, Westland.

The Franz Josef glacier has exhibited a wide range of historical behaviour, with rapid retreat interspersed with short-lived advances from 1850 to 1985, and continuing strong advance from 1985 to the present. This recent behaviour follows the longer-term retreat of the glacier terminus from its position at the coast during the last Ice Age about 20,000 years ago; since that time the sediment delivered by the river has built up the alluvial fan now used by local farmers and tourists.

The area is crossed by the active Alpine Fault, a tectonic feature with a lateral throw of about 450 km and associated current uplift of the order of 0.01 m per year (Adams, 1980). The resulting combination of steep terrain, high rainfall and glaciation results in some of the highest erosion rates in the world. The steep, rapid rivers of the region carry very high sediment loads and build prominent, active alluvial fans where they emerge from the mountains to flow west across the narrow (about 10 km wide) coastal plain to the Tasman Sea. In the smaller streams debris flows are common, while the shattered bedrock of the region, together with the rapid incision of streams and recent deglaciation, give rise to frequent landslides that deliver large quantities of material to the valleys. Earthquakes are clearly a major factor in the land-forming processes, but there has been a peculiar dearth of severe earthquakes in this region in historical times. Whether this is due to long-term, as yet unreleased stress along the Alpine Fault, or whether it is due to continuous, creeping stress release is as yet undetermined (but clearly of more than passing interest); the former seems more likely (Bull, 1996).

The vegetation of the area reflects the mild climate and high rainfall; dense rain forest covers the lower slopes of the mountains, though most of it has been cleared from the flat fans of the lowlands for agriculture. Above the tree-line subalpine scrub predominates; higher still native grasses clothe ridges and basins, while bare rock, ice and scree dominate the landscape at the highest altitudes. At all levels, frequent slips and landslide scars reveal the underlying rock; at lower levels they are rapidly revegetated (Hovius *et al.*, 1997). There are large areas of bare rock in the major glaciated valley of the Waiho River. On the cleared flats, European grasses predominate, though bracken, gorse and matagouri quickly colonise poorly-maintained pasture.

Socio-economic setting

Franz Josef Glacier is a settlement with about 150 permanent inhabitants, increasing to about 750 by tourists in summer. It is one of the two major national and international tourist destinations on the popular West Coast circuit, the other being Fox Glacier about 25 km (and 45 minutes by steep, winding road) to the south. The permanent residents depend on tourism, served by both commercial operators and by the Government-run Department of Conservation, and on cattle farming on the Waiho flats for their livelihoods. Government subsidy of farming once contributed substantially to the economy of the area, but now the subsidies have ended it is doubtful if the settlement would survive without the current boom in tourism. The area was once the site of a gold rush, but mining and the other major West Coast industry, forestry, are no longer significant in the Franz Josef area, as the presence of the world-renowned Westland National Park precludes these activities. As in most of the West Coast, there is an air of independence and of the frontier about the Waiho area, born of the incredible hardships suffered by the ancestors of many of the permanent inhabitants not so many decades ago, the evident power and majesty of the mountains in which many local people earn their living, and of the weather which, though mild, can unleash storms of frightening intensity. This air of independence is reflected in the personalities of the locals who are often strong-minded, individualistic people with a certain impatience towards "city" attitudes and sophistications.

There has for centuries been a Maori presence in the region, but according to local *Tangata Whenua* the Maori population has always been sparse and there are no sites of spiritual or other significance that could constrain resource use. Nevertheless, it is important to recognise that Maori consider certain practices to be unacceptable, for example inter-basin water transfer or discharge of human effluent into waterways, and that the Resource Management Act (1991) requires that these values be taken into account in resource use decisions.

Major facilities and problems

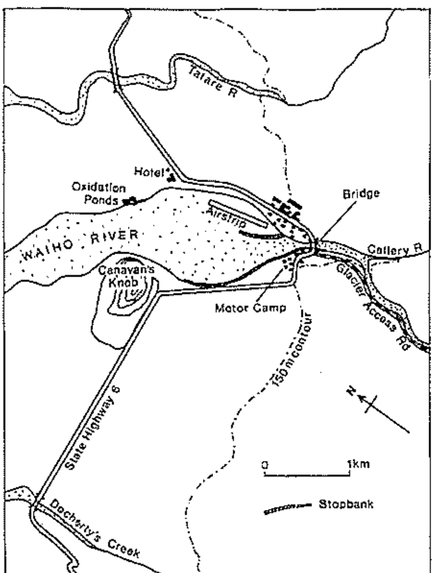

Figure 2 – Locality of Franz Josef township, showing facilities at risk.

The *main highway (SH 6)* is vital to the economy of the area, being the only way by which most tourists can reach Franz Josef and by which agricultural produce can leave. From time to time it is closed due to small landslides and bridge washouts for up to a few days or (exceptionally) weeks at a time; the roading agency, Transit New Zealand, gives very high priority to reopening the road as there is no alternative highway along the West Coast. The highway is particularly susceptible to damage by the Waiho River if the stopbank on the true left of the river downstream of the holiday park area is breached or overtopped.

The SH 6 *bridge* over the Waiho river is equally crucial for the same reasons and is threatened during high flows if the riverbed aggrades or widens significantly.

The *airstrip* at Franz Josef is used for mountain and glacier sightseeing trips in helicopters; a small number of tourists flying into the area also use the airstrip. It is sited close to the township centre, on what was until very recently part of the active riverbed a short distance downstream of the Waiho bridge on the true right side of the river. The airstrip is protected by a large stopbank.

The *holiday park* is the main budget-price accommodation in the area and is very popular with the increasing numbers of backpackers and independent motor tourists visiting the West Coast. Sited at the south end of the Waiho road bridge, it is protected by a stopbank, but is liable to inundation at high flood levels.

The *oxidation ponds* that treat the sewage effluent from the township are situated on the true right bank of the Waiho River, about 3 km downstream from the road bridge. If these ponds should be inundated the township would be left without sewage treatment and, unless it were considered appropriate to discharge untreated sewage directly into the Waiho River, this would require the township to be evacuated.

The *lower township area*, with several hotels, shops and other operations as well as dwellings, is sited on the true right bank of the Waiho River, and is thus vulnerable to erosion by the river if the stopbank protecting the airstrip is breached. In particular, the Franz Josef Glacier Hotel, about 2 km downstream of the road bridge, has for some time been threatened by erosion.

The *glacier access road* begins at the SH 6 road bridge and runs up the true left bank of the Waiho River for about 5 km. It is often threatened, and sometimes closed, by erosion by high river flows. Access to the glacier is very important to tourism in the township; if it were cut off for a long period, many tourists would prefer to stay at Fox Glacier and visit the equally spectacular glacier there, but access to the Fox glacier is presently even more doubtful than to the Franz Josef, due to frequent rockfalls in the glacier valley.

Waiho River system

Figure 1 illustrates the catchment and fan system of the Waiho River. The total catchment area of 162 km^2 above the SH6 bridge includes the Franz Josef glacier/Waiho subcatchment of 70 km^2 and the Callery subcatchment of 92 km^2, of which 13 km^2 and 17 km^2 respectively are ice-covered (Hoey, 1990). The Callery catchment is complex, with three glaciated tributary catchments above the 10 km long Callery Gorge, a deeply incised steep valley that is one of only two remaining uncollapsed slot gorges on the West Coast (T.Chinn, Crown Research, Dunedin, *pers. comm.* 1995). The Callery flows into the Waiho about 500 m above the SH 6 road bridge, emerging from a deeply-cut vegetated rock gorge that makes the confluence inconspicuous.

The Waiho catchment contains the Franz Josef glacier and the proglacial Waiho River. The glacier is the main source of sediment for this river, although occasional rockfalls deposit large volumes of sediment directly into the river valley (Mosley, 1983). By contrast with the steep, narrow Callery valley, the Waiho valley is about 300 m wide below the glacier terminus, with a large area available for sediment storage.

Immediately below the confluence with the Callery, the Waiho flows through a narrow section formed by a 10 m high terrace on the true right (north) and by the southern bridge approaches on the south side. This section is spanned by the road bridge.

Immediately below this narrow section the river bed broadens out to the head of the alluvial fan that extends to the coast. Typical of such landforms, the river on the fan is strongly braided, and the positions of the major channels change rapidly and unpredictably. The river on the upper fan is presently confined to a minor (northern) part of the whole fan area by control banks ("stopbanks" in local parlance). Prominent features of the fan are Canavans Knob, a bedrock knoll on the present left bank of the river about 2 km below the bridge, and the ancient (ca.11,000 years B.P.; Mercer, 1988) terminal moraine known as the Waiho Loop about 5 km below the bridge. It is clear that in earlier times prior to European settlement the Waiho has flowed through gaps in the Loop, to the south of Canavans Knob, and has also joined with the Tatare River to the north and with Docherty's Creek to the south (at present both the Tatare River and Docherty's Creek flow into the Waiho below the Loop, Fig.1).

Sediment eroded from the uplifting mountains is moved out of the mountain catchments onto the fan (and eventually into the sea) by rainfall- and snowmelt-generated river flow. This process is governed by the capacity of the river flow at a particular location to transport sediment compared with the rate at which sediment is supplied to it at that place, either from upstream or from upslope. If the rate of supply exceeds the transport capacity at a river section, local aggradation of the river bed will result; if less sediment is supplied than the river can transport, it will erode sediment from its bed and degradation will result. In general the transport capacity of a river flow varies with the product of flow rate and bed slope of the river (Davies, 1988). This simple picture is somewhat complicated by sediment storage: sediment can remain stationary on the flood plain of a river for some time before it is moved farther downstream. For example, excess sediment delivered to the Waiho by the Franz Josef glacier tends to be immediately deposited on the wide plain below the glacier terminus, while the river removes sediment only at its transport capacity. Thus the river downstream cannot be heavily overloaded by sediment from this source. By contrast, sediment entering the Callery cannot be stored because there is no flood plain; excess sediment will immediately be deposited on the bed of the river, increasing the bed level and slope until the flow has the ability to move it. A large sediment input to the Callery will thus move rapidly down through the gorge and out into the Waiho.

In a river system that is in long-term equilibrium, the river will form its bed so as to be able to transport the sediment supplied to it with the water supplied to it. Water and sediment supply are however rarely steady, so temporary mismatches between them will commonly result in temporary aggradation and degradation here and there in the system. Where an alluvial fan is building, the transport capacity is insufficient to remove the sediment supplied, resulting in long-term aggradation over the whole fan, perhaps interrupted by short-term degradation reflected by the presence of a fan-head trench (Zarn and Davies, 1994).

The Waiho River system has been building a fan since the end of the last Ice Age. During that time the glaciers have retreated from the coast to deep within the mountains, and vast quantities of sediment have been moved out of the mountains to form the coastal plain as a series of coalescing alluvial fans. The general lack of well-defined fanhead trenches on the West Coast suggests that aggradation is still dominant in the area. Thus, in the long term, it is expected that the Waiho River will continue to aggrade its river bed as it leaves the confined valleys of the mountains and emerges onto its fan.

It is known that the Waiho has in the recent past been much more deeply incised at the road bridge site than it is at present. Mosley (1983) records that in the 1850s the river at this section was several metres higher than in 1983, and also much wider (about 140 m), giving rise to the "1850s" terrace; however between 1920 and 1950 the river was deeply incised here (perhaps due to the presence of a large proglacial lake acting as a sediment trap), and when the road bridge was built the bed was several metres below the 1983 level.

On natural alluvial fans the river shifts across all parts of the fan, depositing sediment and building up the whole fan surface gradually. Zarn and Davies (1994) showed that laboratory fans do this by building up opposite sides of the fan alternately; that is, one side will aggrade until it is significantly above the level of the other side, whereupon the flow will switch to the other side and build that up. While this well-defined behaviour might not be prominent under field conditions, such trends might well underlie the behaviour of the Waiho fan.

As the river is aggrading at the bridge section, it is to be expected that the active river bed would tend to widen there. This happened spectacularly during a flood in December 1995 when a 15 m wide by 10 m high by 200m long section of the true right (north) bank was removed by the river. Since the true right bank at this section is now strongly protected, widening will in future tend to erode the less well protected true left (south) bank.

Prediction of river behaviour

There have been three recent attempts to predict likely future aggradation or degradation at the road bridge section of the Waiho. All three have linked river behaviour to the behaviour of the glacier and the location of its terminus; none foresaw the continuation of the 1985–90 advance into the mid–1990s, or the extent of that advance (more than one kilometre to date).

Mosley (1983) expected the river "...to remain unstable", i.e. with short episodes of aggradation and degradation, because he considered that a prolonged advance of the glacier beyond its (1983) location in a rock gorge was unlikely. The river would therefore respond promptly to rockfalls and major storms. Prolonged aggradation was not expected to occur.

Hoey (1990) concluded that "...continued aggradation...is likely, if not inevitable", on the basis that more of the sediment causing aggradation enters from the Callery than from the Waiho, and that the sediment supply from the Franz Josef glacier was likely to decrease once retreat resumed.

Thompson (1991) considered that short-term aggradation would be followed by longer-term (5 to 100 years) degradation, based on interpretation of detailed behaviour of channels on the fan as indicating headward retreat of incision to the road bridge section.

In fact, during the period 1990–98 the glacier has continued its late 1980s advance and is now encroaching into the wide valley above Sentinel rock; this valley surface has aggraded substantially and also steepened during this time. The advance shows no signs of slowing, and seems to be part of a general trend of advance in New Zealand glaciers without proglacial lakes (Chinn, 1994). The river bed at the road bridge aggraded rapidly in 1994, following degradation in 1991 that was probably associated with river control works being installed downstream. Since 1994 aggradation has continued, particularly in December 1995 when 15 m of the high moraine terrace at the north end of the road bridge was eroded. Thus none of the three scientific investigations drew conclusions based on correct interpretation of the system behaviour.

The apparent failure of these scientific predictions is hardly surprising; the only available information about the past behaviour of the system is descriptions of the glacier terminus location at various times in the past and of the bed level at the road bridge. Neither of these can be related to accurate precipitation and temperature data, or to river flows and sediment input data. There are simply not adequate data on which to base reliable predictions, even if the basic principles underlying the behaviour of such complex natural systems were understood – which, it is becoming apparent, they are not (Haff, 1996). It is unlikely that reliable predictions of aggradation at the bridge will become available to aid decision-making about resource use or hazard mitigation in the foreseeable future. A comprehensive interdisciplinary investigation of the meteorological and tectonic inputs to, and sediment outputs from, the Waiho system would however provide a much better background of knowledge for such decision-making.

Human use of the Waiho fan

The magnificent scenery of Westland National Park and the unusual accessibility of the Franz Josef glacier make this a major tourist attraction. This requires facilities to allow tourists access to the region and to the sights, however the dynamic landscape also presents severe hazards for the facilities and their users. The same problems apply, but less intensely, to the agricultural use of the flat land on the fan.

In order to access the area and the glacier, fixed facilities are needed in the form of roads, bridges and accommodation buildings. Such facilities must be located either where they will not be affected by the natural system behaviour, or where the system behaviour can be modified reliably by technology (e.g. stopbanks) to reduce the threat of damage. In the past the tendency throughout New Zealand has been to try to modify the system behaviour, but it is now recognised that this strategy is neither sustainable nor economic (Erickson, 1986; Davies and Hall, 1992); this is particularly true in an environment as powerful as that at Franz Josef. The locations chosen for facilities, mostly in the first half of this century, are increasingly becoming untenable in the face of the river behaviour. To date, attempts to redress the situation have consisted of augmenting the protection works (e.g. raising and/or rebuilding stopbanks) or raising the bridge (as in 1993), rather than seeking a longer-term solution by relocating facilities beyond the reach of the river. This could be because of the high immediate cost of the relocation, and in spite of its overwhelming longer-term benefits. Many believe (or hope) that the present river behaviour is unusual and will change in the near future; they do not appreciate the basic aggradational behaviour of fan systems.

In an area where the river behaviour is intrinsically very difficult to predict, a management strategy is needed that can deal with the worst-case scenario for river behaviour, but which can be implemented incrementally so that particular measures are brought in only when it is apparent that they will be needed in the near future.

River behaviour scenarios

The worst-case scenario for the future is that the river will continue to aggrade rapidly. The threat to the facilities will then quickly become so severe that they will become unusable. There is no effective river control measure that can prevent a river from aggrading if that is its natural tendency; restricting the channel width has been shown to be ineffective in inducing degradation and, in fact, to exacerbate the problem in many cases by concentrating aggradation on a small part of the original river bed and hence increasing the rate of bed level rise (Davies and Lee, 1988). In this scenario the only way the facilities can continue to be used is if they are relocated beyond the reach of the aggrading river.

For the worst case scenario, therefore, it is necessary to develop contingency plans for the relocation of the state highway south of the bridge, the bridge itself, the holiday park, the airstrip, the oxidation ponds, the Franz Josef Hotel and the lower part of the township.

The best-case scenario is that the river will begin to degrade immediately and continue to do so in the long term. Since the cause of the present aggradation is unclear, so are the circumstances under which this best-case scenario might occur. Coping with it would require very little action, apart being aware of the danger that river control works might become undermined and require strengthening.

Intermediate scenarios take the form of more or less rapid and perhaps intermittent aggradation, in which case the question becomes the order in which facilities will need to be relocated, and to where. To address this requires appreciation of the nature of the hazards, i.e. how will facilities be affected by continued aggradation?

Natural hazards at Franz Josef

The two main threats to life and facilities at Franz Josef are earthquakes and floods. The earthquake hazard is difficult to estimate clearly, but it is evident that there have in the past been major movements along the Alpine Fault in this area. Adams (1980), based on a study of river terrace geometry, states that the average recurrence interval for major movements is 500 years, with a maximum displacement of about 9 m, and an earthquake magnitude of about 8.1; the last event was about 550 years ago. Bull (1996) presents evidence based on lichenometry that fault movements of this magnitude occur at regular intervals of close to 260 years, the last being about 250 years ago. Such an event will cause major destruction at Franz Josef, due in part to landslides, some of which may block the Waiho or Callery rivers and cause dambreak flooding. Plans for coping with such a major earthquake are beyond the scope of this paper; such an event will cause serious destruction far beyond the West Coast, and will be a national catastrophe, so there is an urgent need for contingency planning.

The flood hazard at Franz Josef is also difficult to predict in terms of maximum magnitude and time of occurrence, but is easier to avoid. Continued aggradation of the river bed will gradually increase the maximum water surface elevation of floods, so that flood discharges which presently do not overtop the flood banks will overtop them in the future. Minor floods that occur several times a year are not the greatest danger; the rarer, greater flood flows present serious hazard because they happen infrequently and may overtop flood banks by a large margin, inundating places where flooding is not anticipated. As aggradation continues, larger overflows will occur with smaller and smaller floods.

There are three potential causes for major floods at Franz Josef: heavy rain, glacier burst ("jökullhlaup") and the breaching of a landslide-created dam.

Floods caused by heavy rain are part of a continuous population of events and can be analysed using records for the past flow of the river, assuming that such records are available and that the past rainfalls are statistically equivalent to those in the future. Unfortunately neither of these assumptions is valid for the Waiho; there are no long-term flow records for the river, and there is evidence that average winter rainfall at Franz Josef is increasing with time, being 20% greater at present than 60 years ago (S.Larsen, Department of Natural Resources Engineering, Lincoln University, *pers. comm.* 1996). Nevertheless there is a local appreciation of rainfall-induced floods, and some very rough knowledge of the rainfall intensities and temporal storm patterns that tend to cause the biggest river flows (Thompson, 1991). There is thus some possibility of at least avoiding loss of life by evacuation of endangered properties when rainfalls look threatening.

Glacier-burst floods, on the other hand, are poorly understood. They apparently result from some structural failure of glacier ice (usually during a storm) allowing water and sediment stored within the glacier to be released suddenly to the proglacial river, along with large quantities of small icebergs. Unanticipated and very sudden increases in downstream water level can result; hence evacuation is not feasible unless the event is detected at the glacier and immediately reported to Civil Defence. This is unlikely to happen unless a specific warning system is set up, and even that may be unreliable at night in storm conditions. Glacier bursts are rare but do present a real hazard that is all the more dangerous for being unusual and poorly understood. As with rain floods, the danger to facilities and life increases as the river bed aggrades. The only effective safety measure is to completely avoid such floods by relocating facilities.

The most potentially dangerous flood hazard of all, almost completely unrecognised locally, is the occurrence of flood caused by the overtopping and failure of a landslide dam in the Callery gorge (Costa and Schuster, 1988; Scott, 1996; Davies and Scott, 1997). A major slope failure in the Callery gorge could form a temporary dam, blocking the flow of the Callery and forming a lake. When the lake level overtops the crest of the dam, the dam will rapidly erode and the lake will rapidly drain, sending a very large flood wave down the Callery. This will emerge into the Waiho just upstream of the road bridge, probably carrying with it a very large quantity of debris, and will certainly threaten the holiday park area and road bridge with destruction (Scott, 1996). There is historical and sedimentary evidence (Davies and Scott, 1997) that such events have occurred in the past. Aerial photographs reveal locations with a high probability of future slope failures, initiated either by rain or by earthquakes. Because the formation of a landslide dam will cause the flow rate in the Callery to *fall* temporarily, and because the Callery gorge is almost completely inaccessible, there is little chance of detecting the event and issuing timely evacuation orders unless specific measures are put in place for this purpose.

The probability of a landslide dambreak flood occurring in any given year is about 1% (Davies and Scott, 1997). This is considerably greater than the normal acceptable risk from collapse of an artificial dam with similar consequences. It is not feasible to construct protection works, because of the magnitude of the flood. Although the probability of a glacier-burst flood is less well-defined, it is certainly greater than zero and is additional to the dambreak flood risk.

The probability of a glacier-burst or landslide dambreak floods is so high, and these events will have such serious consequences, that it is difficult to avoid the conclusion that the facilities most threatened should immediately be relocated. This applies in particular to the area immediately south of the SH 6 bridge, which is very susceptible to inundation by normal flooding and to destruction (with the potential for the loss of many lives) by glacier-burst and landslide-dambreak floods.

Next on the list of susceptible facilities is the highway bridge, which is clearly at risk of damage or destruction by all types of flood. It may well be possible to relocate it at a higher elevation at its present site, unless or until aggradation becomes so severe as to necessitate finding another site.

The stopbanks that protect the airstrip and the highway south of the bridge are also threatened with overtopping and destruction by floods. Here loss of life is less likely, but if the river breaks out and flows to the south of Canavans Knob it could destroy several kilometres of highway, and the river will be very difficult to relocate back in its present bed. A large area of farmland and several dwellings will also be affected, perhaps permanently. A breakout to the north will destroy the airstrip and will begin to erode the lower part of the township, the hotel and the oxidation ponds, again threatening some loss of life in a sudden major flood and serious loss of amenities. Damage to the oxidation ponds might necessitate evacuation of the township until sewage treatment services could be restored.

Long-term management

The management plan outlined in this section is not the only such plan that could be devised, nor is it necessarily the best; the objective is to demonstrate that such a plan can be developed. No planning detail is attempted, this being outside both the scope of this work and the expertise of the writer. The plan does not attempt to control or oppose the natural processes of the area, and it recognises the possibility of unexpected changes in behaviour of the river and glacier and the catastrophic hazard posed by glacier-burst and landslide dambreak floods. It can be implemented in stages as and when required, but the planning, design and consents process would need to be gone through at an early stage so that when a particular stage becomes necessary it can be implemented without delay.

The objectives of the strategy are, first, to eliminate as far as possible the threat to life and facilities posed by the present and future behaviour of the Waiho River; and, second, to ensure continued use of the facilities, in particular the road, without which the area will become economically and socially bankrupt.

The basis of the strategy is that, accepting that continued aggradation of the river will result in it moving its bed to occupy a different sector of its fan as outlined by Zarn and Davies (1994), it is preferable that the river re-occupy the southern sector in the near future, thus moving the river away from the concentration of facilities in the vicinity of the north bank for a considerable time. In this way it might *not* prove necessary to relocate the airstrip, hotel, oxidation ponds and lower township in the foreseeable future, though planning for relocation or alternative facilities should proceed.

Stage 1: Immediate:

(a) Relocate the holiday park and adjacent buildings to safe sites, preferably to the north of the township; zone the land adjacent to the southern stopbank as far as Canavan's Knob as non-residential.

(b) Carry out feasibility studies of alternative bridge sites, and of road alignments south of the bridge, leading to the design of new bridge(s) and roadway and obtaining of resource consents. Severe aggradation could eventually make the present bridge site unusable; one obvious alternative would be to cross the Callery just above its confluence with the Waiho and the Waiho just west of this.

South of the present bridge the road could be relocated along the 150 m contour, above flood level, to cross Docherty's Creek above the present road crossing. This is within the National Park and close to the trace of the Alpine Fault, but given the lack of alternative alignments and the impossibility of avoiding earthquake-susceptible locations in this area, this possibility has to be considered seriously.

(c) Plan to raise the present bridge and approaches to the maximum possible extent when required.

(d) Investigate potential new locations for oxidation ponds or an alternative treatment method (e.g. septic tanks) and obtain the necessary consents.

(e) Strengthen, raise, and/or lengthen the stopbank protecting the airstrip and township.

Stage 2: When the Waiho River overtops or breaks through the stopbank south of the bridge, or such events are expected soon:

(a) Construct a new road along the 150 m contour to Docherty's Creek, joining the present road above the Creek.
(b) Relocate dwellings in threatened areas of Waiho Flats.
(c) Plan to realign the road north of the Waiho River to access the new bridge site, and south of the river to join the new bridge to the new road in 2(a).

Stage 3: When the present bridge site becomes unusable:

(a) Commission new bridge(s) at an alternate site, with new approaches linking it to the township and the realigned road south of the river.
(b) Commission a new glacier access road from the new bridge site.

This is a radical strategy and may not be acceptable until the local community and the agencies responsible for land use and tourism in the area can be convinced of the potential dangers outlined above and take responsibility for their mitigation. In particular the need to relocate facilities that are on private land with current use consents, or where the preferable alternative locations are already occupied, will require legal action of some sort.

The intention of this report is to suggest a flexible plan that allows continued, long-term use of the area's natural resources. Particular hazards are avoided only as (and if) they become critical due to continued river aggradation. Hazards with the potential to be catastrophic, however, are avoided immediately by relocating threatened facilities. The total cost of implementing this strategy is considerable, but it is spread over a long period. Implementation of any specific measure is subject to a considered decision at the time. In particular, if the behaviour of the system *does* change in the future, for example the river bed elevation at the bridge ceases to increase, the measure can be halted and further steps held in abeyance, perhaps for a very long time.

For such a strategy to become accepted, the futility of attempting to control the natural processes of the landscape must be accepted. Managers now realise that they cannot reliably control the behaviour of a river as powerful as the Waiho; only by respecting the natural tendencies of the system is it possible to influence the future location of the river on its fan and continue to use the resources of the system in the long term.

The above strategy is also only an outline; many important details would need to be considered even at preliminary stages, requiring input from experts in many fields. However the fundamental realities of the susceptibility of facilities to serious damage; of the exposure of people to loss of life; and of the absolute vulnerability of the area to the security of SH 6 are unarguable and must be the focus of any management strategy.

Conclusion

At Franz Josef a powerful, complex and poorly understood natural system (the landscape of Westland National Park) is being used by a less powerful but complex human system (Franz Josef township) to generate wealth (both economic and spiritual); the future interactions between these two systems need to be very carefully considered if wealth generation is to continue in a sustainable manner. The behaviour of the natural system (in particular the Waiho River) is dangerous because it is *not* reliably predictable, nor can it be readily controlled. Therefore, if a future catastrophe is to be avoided, the behaviour of the human system must adapt to the behaviour of the natural system rather than vice versa; existing facilities must be moved out of harm's way. The facilities at greatest risk, those on the south bank of the Waiho, should be relocated first – if the river is allowed to re-occupy this area, it may forestall the later need to relocate facilities on the river's north bank.

The abilities of present and future generations to satisfy their needs in this area are severely limited by the behaviour of the natural system. The strategies developed for resource use and hazard mitigation must therefore be precautionary and remain under continuous review, informed by continuous monitoring of the natural system and by continued attempts to improve understanding of its behaviour.

Acknowledgements

The source of much of the material developed herein is three years (1994–96) of project reports of students in their final year of the BE (Natural Resources) degree course at Lincoln University. I am deeply indebted to these students for their interest, their ideas and their ability to research both social and physical aspects of the Franz Josef area in the very limited time allowed to them.

I am also deeply indebted to Alex Miller of Docherty's Creek for many years of perspicacious and common-sense comment on all aspects of the local situation, and to his wife Suzy for clear insights into the environmental aspects of proposed developments.

Mauri McSaveney (IGNS Lower Hutt) has provided invaluable perspectives on the geological and geomorphic processes likely to be relevant, and reviews of the manuscript by him and Linton Clarke have improved it considerably.

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Manuscript received: 6 January 1997; accepted for publication: 30 June 1997.