Journal of Hydrology (NZ) 36(1): 1-13, 1997

Dambreak flood hazard from the Callery River, Westland, New Zealand

T. R. Davies

Dept. of Natural Resources Engineering, Lincoln University, Canterbury

B. K. Scott

Beca Carter Hollings and Ferner Ltd, PO Box 3942 Wellington

Abstract

The Callery River, Westland, is a right-bank tributary of the Waiho River and enters the Waiho immediately above the township of Franz Josef Glacier. The lower 10 km of the Callery flows in a deep, steep-sided gorge susceptible to landsliding from heavy rain, earthquakes, and slope undercutting. These factors all suggest that it is likely to experience floods caused by the formation and collapse of natural dams created by landslides from the gorge walls. There is evidence that such events have occurred in the past, and likely sites for future large landslides can be identified. The magnitude of potential landslide dambreak floods is of the order of several thousand cubic metres per second, compared with a 0.01 annual exceedence probability (aep) discharge of the order of 1 300 m^3s^{-1}; the annual probability of a dambreak flood event is about 1%. The impact of a landslide dambreak flood on the Franz Josef area would be severe. Sufficiently early warning of such a flood, so that evacuation could be carried out, could not be guaranteed. The most realistic mitigation strategies therefore involve restrictions on land use so that facilities and lives cease to be at risk.

Introduction

The lower 10 km of the Callery River (a right bank tributary of the Waiho River, Westland) flows in a deep, narrow gorge close to the Alpine Fault. Much of its catchment lies in the region of very high rainfall to the west of the Main Divide. The combination of very steep terrain with high relief, tectonic activity and high rainfall suggest that landslides into the gorge could temporarily dam the river. Were this to occur, the dam could fail rapidly when overtopped, giving rise to a flood wave moving down the gorge and exiting into the Waiho River just above Franz Josef township.

This paper investigates this possibility, estimates the peak flow rates that could arise and the probability of their occurrence, assesses the nature and intensity of the hazard that such an event could produce, and considers the measures available to mitigate its effects.

Physical setting

The Callery River, Westland (Fig. 1), rises to the west of the Main Divide in the vicinity of Mt Elie de Beaumont. The total catchment area is 92 km^2, of which about 17 km^2 are ice-covered (Hoey, 1990). Its upper basins extend to over 3 000 m altitude, and comprise the Spencer, Burton and Callery glacier valleys, which join to form the lower gorged reach of the Callery. This reach extends through a distance of about 10 km, which is an unusually long gorge even in this very active landscape. The gorge has very steep (about 45°) and high (up to 1 000 m) side slopes of mainly linear profile, which indicates recent and continuing active incision (Finlayson and Statham, 1980). The dominant slope erosion process is clearly that of surficial landsliding (Hovius *et al.*, in press), together with larger, more deeply-seated failures in bedrock caused by basal

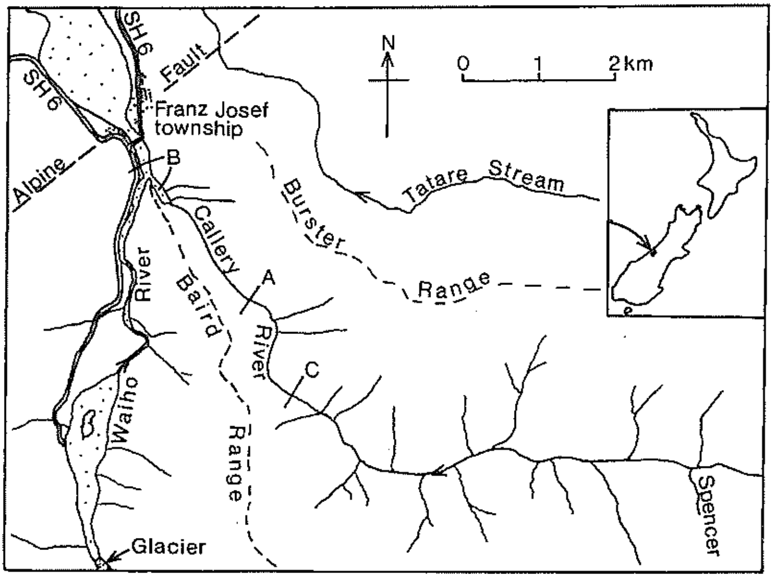

Figure 1 - Map of the Callery River and the Franz Josef township area.
A - Possible landslide dam remnant (see Fig. 3a)
B - Possible landslide dambreak flood terrace remnants (see Fig. 3b)
C - Potential landslide dam site (see Fig. 4)

oversteepening, intense rainfall and/or earthquake shaking. The river itself flows in places in a deep box canyon at the base of the side slopes. The longitudinal profile of the river is remarkably even through the gorge; local steepening between 9 and 12 km upstream of the Waiho confluence probably results from massive prehistoric landsliding (Fig. 2).

The catchment and gorge were occupied by glaciers during the last ice age, and the gorge must have been abandoned by ice during the last few thousand years. It is an indication of the intensity of postglacial erosion that little evidence of glacial action remains in the gorge reach of the river.

The bedrock of the area is foliated schist. The Alpine Fault, which passes about 1 km west of the Waiho-Callery confluence (Fig. 1), has been inferred to suffer major movements every 260 (± 15) years. They typically result in lateral displacements of about 8 m and vertical displacements of about 2.5 m. The magnitudes of these earthquakes will be greater than M = 8 (Bull, 1996; Adams, 1980).

In the absence of hydrological data from the Callery, it is assumed that precipitation in the catchment headwaters approaches 11 000 mm a^{-1}, as in other similar catchments in the vicinity (Griffiths and McSaveney, 1983). Above about 1 500 m some of this falls as snow, especially in winter. The mean annual flood in the Callery has been estimated as about 600 m^3s^{-1}, and the 0.01 aep flood as about 1 300 m^3s^{-1} (Scott, 1996). Normal (mean annual) flow is of the order of 25 m^3s^{-1}.

The Waiho River has a catchment area of 70 km^2 at the Callery confluence, 13 km^2 of which is glaciated. The Waiho rises in the Franz Josef glacier and flows past Franz Josef township to the Tasman Sea across

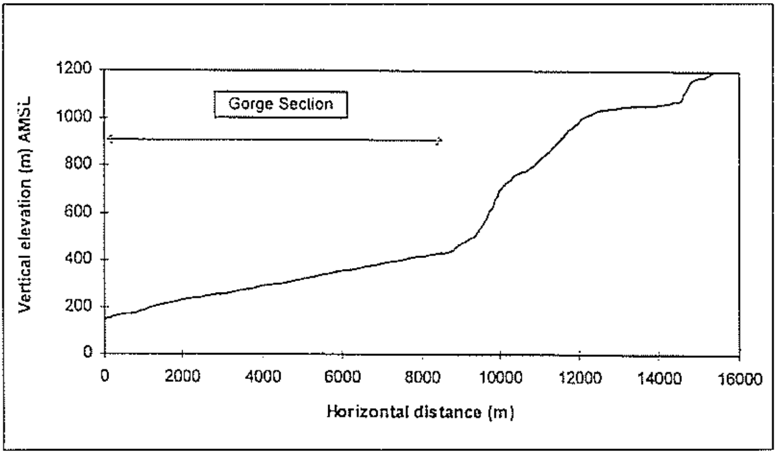

Figure 2 - Longitudinal section of the Callery River

an elongated alluvial fan occupying the former trough of the glacier. Tourism facilities in the vicinity of Franz Josef township are at risk from aggradation and flooding in the Waiho (Davies, in prep.) and are thus liable to be damaged by dambreak floods from the Callery should they occur.

Landslide dams

Costa and Schuster (1988) surveyed data available worldwide on the formation of natural dams and the floods resulting from their failure. They found that 90% of landslide dams are caused by either rainfall or earthquake, and that they form most frequently where narrow, steep valleys are bordered by high rugged mountains. In such situations relatively small landslides can form dams sufficiently high to impound substantial volumes of water.

Not all landslide dams fail; some create lakes that become long-term features of the landscape (Adams, 1981; Perrin and Hancox, 1991). Outflow from such lakes is often by seepage through high-permeability rock debris. Those dams that fail do so mostly (95%) as a result of overtopping and erosion of the downstream face, but a small proportion fail by piping or downstream slope failure without overtopping.

Half of all landslide dam failures occur within a week of the landslide; a quarter within one day. This high proportion of early failures is presumably related to rainfall-generated landslides and rapid overtopping of the dam by high river flows. A total of 85% of all failures occur within 1 year of formation.

A recent example of a landslide dambreak flood in New Zealand is the Tunawaea event in the King country in 1991 (Webby and Jennings, 1994). This landslide dam failed during a rainstorm 11 months after emplacement, probably by overtopping. The peak discharge (estimated using a computer model) was close to that predicted by Eq.1 below.

From this brief summary it is clear the Callery River is a likely site for the formation of a landslide dam, due to the steepness, depth and length of the gorge. When such an event occurs it is likely that the dam will overtop and fail very soon after emplacement.

Landslide dambreak floods

Costa (1985) reported the magnitude of the flood discharges caused by failure of landslide dams throughout the world. He presented three regression equations, the most satisfactory of which relates peak flood discharge (m^3s^{-1}) to the product of dam height and stored water volume:

$$Q_{max} = 181(HV)^{0.43}\ ;\ r^2 = 0.76, SE = 129\% \qquad (1)$$

where H = dam height in metres, V = stored water volume in $m^3 \times 10^6$. A notable feature of such floods is that the attenuation of the peak discharge with distance downstream of the dam is quite slow; for example, the Tunawaea dambreak floodwave (Riley *et al.*, 1993) reduced in maximum discharge from 250 m^3s^{-1} to 178 m^3s^{-1} in a distance of 21 km. In addition, it is likely that the outflow of water will entrain substantial quantities of sediment from the dam itself and from the channel banks and bed downstream, causing bulking and discharge increase, with correspondingly high flood levels; in extreme cases a debris flow might result (Costa, 1985). Such a flow emerging from the Callery gorge could leave a substantial sediment deposit; a remnant landform located below the Callery gorge may be such a deposit.

Callery gorge - past events and future dam sites

If the Callery gorge is indeed a likely site for the occurrence of landslide dambreak floods, there should be evidence of such dams having formed and failed in the past. In an environment as geomorphically active as this, however, evidence would tend to be removed very rapidly by subsequent erosion. Inspection of aerial photographs reveals a likely dam remnant about 2 km upstream of the Waiho confluence (Fig. 3a). A landslide appears to have come down the true right slope of the gorge and butted against the true left slope to an elevation of about 400 m asl, which would have created a dam with a height of the order of 180 m. Subsequently the river has incised through the deposit, and the true right slope has yielded all its remnant material to the river. In addition, on the true left bank of the Waiho opposite to and downstream of the Callery confluence is a terrace edge that is sharply concave to the east (Fig. 3b), suggesting that the flow which eroded it came from the direction of the Callery; it is difficult to imagine such erosion being the result of flow coming down the Waiho. This terrace edge also seems to line up with a similar feature on the true left bank of the Callery immediately downstream of the exit from its gorge (Fig. 3b), comprising mixed size, blocky, non-glacially transported material which could be interpreted as a landslide dam failure deposit. This again suggests that a very large flow has emerged from the Callery.

Access to the Callery gorge is extremely difficult due to the rugged terrain and dense vegetation. (Gold miners in the last century gained access to flats in the mid-reaches of the gorge via the top of Mt Burster, 1 400 m asl.) Inspection of aerial photographs reveals several possible future

(a)

(b)

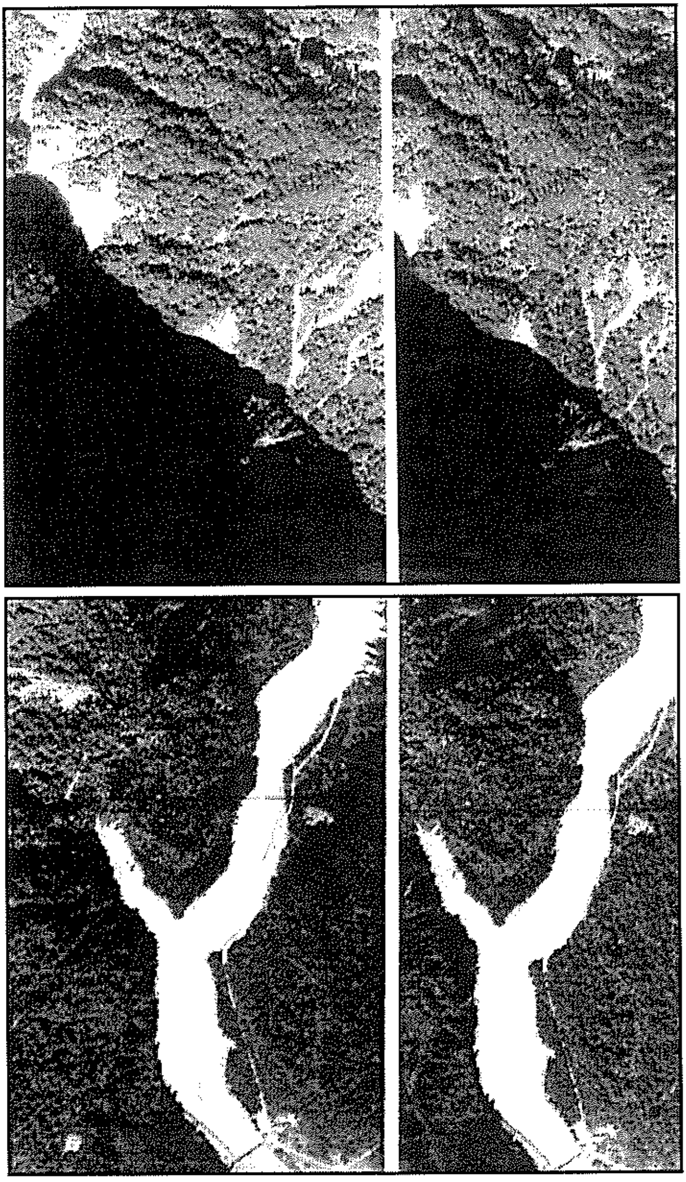

Figure 3 - (a) Stereo photographs (1985) of the Callery gorge about 2 km upstream of the Waiho confluence, showing a possible landslide dam remnant (A in Fig.1). Flow is from top left to bottom right. (b) Stereo photographs (1985) of the Callery/ Waiho confluence, showing terrace remnants of a possible landslide dambreak flood (B in Fig.1). The SH 6 bridge is at the bottom of the field of view, and flow is from top to bottom.

landslide dam sites, based on the visual appearance of the landscape and slope steepness. The most likely site for a major slope failure is about 4 km upstream of the Waiho confluence (Fig. 1), where a faulted block on the true right bank is poised above a very steep, narrow gorge section (Fig. 4). The volume of material involved in this potential landslide is very approximately 0.75 x 10^6 m^3, and reasonable assumptions about upstream and downstream dam slopes would give a dam height of about 90 m at this site. The volume of water that would be stored at crest level would be about 13 x 10^6 m^3. At average flow this reservoir would take about 6 days to fill and overtop, whereas at mean annual flood it would take only about 6 hours (Scott, 1996).

Using Eq.(1), the peak flow rate from the failure of this dam would be of the order of 3 800 m^3s^{-1}. Assuming negligible attenuation in traversing the 4 km of steep, narrow gorge to the confluence, this is also approximately the peak flow rate of the flood wave that would emerge from the gorge into the Waiho (ignoring sediment entrainment, bulking and debris flow generation, all of which would tend to increase the peak flow).

There are other possible dam sites in the gorge, at about 5 and 12 km upstream of the Waiho confluence. Although they involve greater landslide volumes, the dam heights are lower because the valley side slopes are less steep and the stored water volumes would be considerably less than at the lower gorge site. The peak flows resulting from failures at these higher

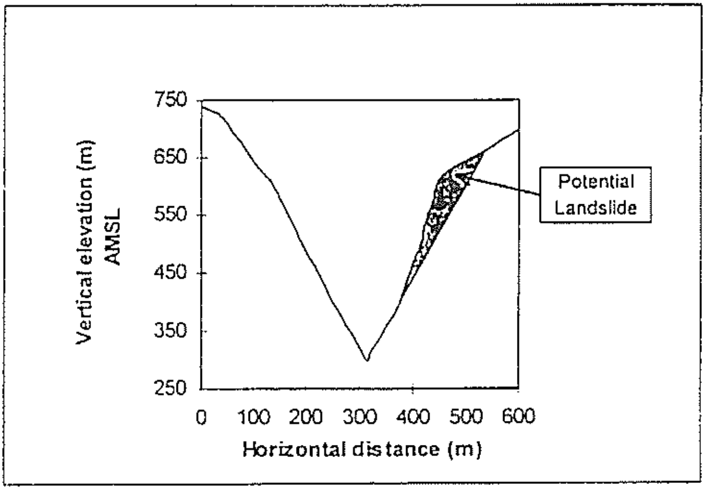

Figure 4 - Cross-section of potential landslide site (C in Fig.1)

sites are estimated to be about 1 400 m^3s^{-1} in both cases, and attenuation in traversing the gorge could be significant in the case of the farthest upstream site (Scott, 1996).

The middle landslide (5 km upstream of the Waiho confluence) is thought to be likely to be triggered by rainfall, since it is the site of an existing slip and at a relatively low angle. The two other sites would seem more likely to be triggered by an earthquake, since they are bedrock sites at which failure is likely to be deep-seated (Scott, 1996).

The peak flow due to the failure of the remnant dam tentatively identified in the lower gorge (Fig. 3a) can also be estimated from Eq.(1); the height of the remnant is about 180 m above the river bed, and the volume of water stored at its crest level would have been about 54.5×10^6 m^3, thus peak discharge would have been about 9 500 m^3s^{-1}. Attenuation of this flood wave would have been negligible in traversing the gorge to the Waiho confluence. A flow of this magnitude would certainly be capable of forming terraces in the glacial deposits of the Waiho valley as inferred above (Fig. 3b).

The calculations of peak discharge above are clearly very approximate, but the flows are so large as to indicate reliably that the flood peaks could reach many thousands of cumecs, and far exceed rainfall-generated flows.

Probability of occurrence

In the absence of any data on the occurrence of landslide dambreak floods from the Callery gorge, it is difficult to calculate a realistic numerical frequency for such an event. From the geomorphic evidence it is reasonably certain that such events have occurred in the past, but the number and timing of these events is unknown.

The order-of-magnitude annual probability p(F) of an earthquake-generated landslide dambreak flood can be estimated by assuming that it is equal to the product of the annual probability of a serious earthquake p(E); given the earthquake, the probability of a landslide into the gorge p(L); and, given the landslide, the probability of the landslide dam being breached p(B). Due to the steepness and depth of the gorge it is assumed that any significant landslide will dam the river.

The magnitude of the probability thus calculated depends very strongly on p(E), the value of which in turn depends on the past history of earthquakes on the Alpine Fault. Historical data would suggest that the Franz Josef area is seismically rather inactive; however, the presence of the Alpine Fault indicates otherwise. Two independent investigations have focused on this issue. Adams (1980) deduced from river terrace geometries that the return interval of major Alpine fault movements was about 500 years, with the latest movement being about 550 years ago. Bull (1996) deduced from analysis of lichen diameters on fallen rocks that the return interval of movement of the Cook segment of the fault was 260 ± 15 years, with the latest event being 240 to 260 years ago. Both these conclusions have similar implications and, while not universally accepted, must be taken seriously when assessing the risk to life that might result. If these results were not available, then one could justifiably assume that p(E) was the reciprocal of return period, or about 0.002 - 0.004. However, it would be unwise to base a risk assessment on such an assumption. A p(E) value of 0.03 is used, based on the high probability that the event will occur during the next 30 years. p(L) in such an event will be high, at least 0.5, while from Costa and Schuster (1988) p(B) is about 0.8. Thus p(F) is $0.03 \times 0.5 \times 0.8 = 0.012$, and there is thus at least a 1% chance of an earthquake-generated landslide dambreak flood every year at present. The probability of rainfall-generated landslide dambreak floods increases this figure by an unknown amount.

This result, though approximate, shows that the risk of a dambreak flood event from the Callery is too great to ignore. The event would be comparable in magnitude and effect to the flood from collapse of a major artificial dam. The acceptable risk for artificial dams can be estimated from the annual exceedence probability of the event which major dams are normally designed to survive. This is usually either 0.0001, corresponding to a 10 000-year event, or the probable maximum flood (which has a zero probability of being exceeded), in cases where failure of the dam will result in loss of life (Singh, 1996). The risk of a landslide dambreak flood in the Callery is thus a least two orders of magnitude greater than the acceptable risk for collapse of an artificial dam in a similar situation.

Consequences of a landslide dambreak flood

The 0.01 aep rain flood flow in the combined Waiho-Callery system at the SH6 bridge (Fig. 1) has been estimated to be about 2 000 m^3s^{-1} (Thompson, 1991). Occurrence of a landslide-dambreak flood with a flow of the order of 3 800 m^3s^{-1} and extremely high sediment load would result in flood levels very considerably in excess of those expected in any rainstorm flood, and would cause substantial damage to local facilities. If the terrace remnants mentioned above are indeed relics of this type of event they give a good idea of the likely effect of such a flood wave.

It is likely that a dambreak flood in the Callery would cause very serious damage and probably loss of life at Franz Josef Glacier township (Davies, in prep.). To clearly assess the hazard zone extent, and the effects on facilities, further work is required to establish the behaviour of a dambreak flood wave entering the Waiho under a range of conditions.

Mitigation strategies

Detection of a landslide dam

Access to the Callery gorge is extremely difficult, and it is likely that a landslide dam could remain undetected unless this eventuality has been foreseen and planned for.

After every major earthquake, efforts must be made to ascertain whether a dam has formed. This might involve using a helicopter for a visual inspection of the valley.

A major warning sign that a landslide has blocked the Callery River will be that the flow is very low and the water is dirty or discoloured. In the aftermath of a severe earthquake, however, people could be too preoccupied to notice this warning sign. A water-level recorder at the lower end of the gorge with an alarm warning of low water-levels would be effective for both earthquake- and rainfall-generated landslide dams. Such a device must be robust enough to function reliably under all circumstances, including backwater from the Waiho River. A comparison water-level transmitter in the Waiho might also be necessary, but would be more difficult to establish, given the braided nature of this river.

Evacuation of riverside buildings

A well-rehearsed evacuation plan should be in place that can be put into effect immediately if a dam is detected or suspected.

One if the major problems in planning to cope with a flood from the Callery gorge caused by a landslide dambreak is that the time between the dam forming and the flood wave reaching Franz Josef township could be very short. If the landslide is triggered by an earthquake during a spell of dry weather, the dam will take some days to fill, giving time to take some action. In wet weather, however, the reservoir could fill very rapidly and the time to failure could be hours rather than days. The travel time of the flood wave through the few kilometres of gorge would be minutes rather than hours.

A lot of time is needed to evacuate occupied buildings and move people to safety, especially if it is dark and/or stormy. People may be frightened (especially in the aftermath of a major earthquake with continuing aftershocks), sleepy, old or infirm. As Franz Josef is a tourist centre, many people there will be visitors unfamiliar with the local area, and some may not speak or understand English. One or two hours may be needed to move a substantial number (perhaps hundreds) of people from riverside accommodation to safety.

Engineering measures

In some cases overseas, floods from landslide dams have been averted by construction of an artificial spillway that allows the dam to be overtopped without failing. This requires heavy equipment to be moved to the dam site prior to failure; in the case of the Callery area this is impossible due to the inaccessible and rugged terrain and the very short time available.

Reducing the number of people and facilities at risk

Given the inaccessibility of the Callery gorge, the difficulties of detecting a landslide dam and the fact that the warning time of a dambreak flood, even with prior warning from a water-level recorder, is likely to be very short - between a few minutes and a few hours - it is questionable whether evacuation will be a reliable and effective mitigation strategy for dambreak floods. Consideration must therefore be given to restrictions on land use, to minimise the number of people occupying the riverside areas most at risk.

In the Franz Josef township, the primary requirement is to establish which facilities would be at risk from a landslide dambreak flood; to establish from which of these the occupants could be evacuated to safety in the warning time available from a water-level alarm device or visual detection of the dam; and to make a serious decision as to whether occupancy of those dwellings that cannot be readily evacuated should be allowed to continue.

In a major earthquake, there are other sites on the West Coast where landslide dambreak floods are a possibility. This study focuses on the Callery because the local topography is unusually favourable for such events; almost any landslide in the 10 km gorge reach will cause a dam to form and fail. Other rivers have much shorter gorges, so the probability of a landslide blocking the whole valley width to a significant depth is much lower; however these sites also need to be investigated.

Conclusion

The probability of a landslide dambreak flood from the Callery river affecting Franz Josef township and its vicinity is presently of the order of 1% per annum. This is much greater than the acceptable risk of an artificial dam collapse, and cannot be ignored. Such an event could well have a peak discharge several times that of the one hundred year rainstorm flood, with correspondingly high flood levels and velocities. It is likely to be undetected before it enters the Waiho River unless specific measures are taken to detect it. Very severe damage to facilities will result from such an event, and lives will be at risk. Urgent action is needed to plan and implement measures to avert the catastrophe which will otherwise result when the event occurs.

Addendum

Recently our attention was drawn (J.Wilshire, Dept. of Geography, University of Canterbury, Private Bag, Christchurch, NZ, *pers. comm.*) to a Report by the residents of Franz Josef township to the Tourist Hotel Corporation, dated 1957 and held in the archives of the Department of Conservation, Franz Josef Glacier. A section of the report headed "Landslides" states:

"Another possible factor contributing to the instability (sic) is the possibility of major landslides in the Callery gorge. One such landslide in 1930 completely blocked the Callery for one day. The resulting flood was extremely high and the debris from these slips, when carried down further adds to the river bed problems."

This event occurred during fine weather, so flow in the Callery on the day of blockage would have been about the mean annual flow of about 25 m^3s^{-1}, and blockage for one day would have stored about 2×10^6 m^3 of water. A landslide dam in the lower gorge would need to be about 50 m high to store this much water, in which case Eq.1 gives a maximum discharge of about 1400 m^3s^{-1}, which would correspond well to an "extremely high" flood at the SH 6 crossing. This record from actual experience supports the main tenet of this paper, that dambreak floods do occur in the Callery and that Eq.1 provides a reasonable estimate of the likely magnitude of the resulting maximum flows. The lack of mention of earthquake in the 1957 Report also suggests that substantial aseismic landslides do occur in the Callery gorge.

Acknowledgements

Assistance with field work was provided by the Department of Conservation, Franz Josef Glacier; Alex Miller of Docherty's Creek provided valuable information about the Callery gorge, and Mauri McSaveney of GNS, Lower Hutt helped with discussion of many of the concepts herein. The comments of two anonymous reviewers led to significant improvements in the manuscript.

References

Adams, J. 1980: Paleoseismicity of the Alpine fault seismic gap, New Zealand. *Geology 8*: 72-76.

Adams, J. 1981: Earthquake-dammed lakes in New Zealand. *Geology 9*: 215-219.

Bull, W.B. 1996: Prehistorical earthquakes on the Alpine fault, New Zealand. *Journal of Geophysical Research 101, B3*: 6037-6050.

Costa, J. 1985: Floods from dam failures. *USGS Open-File Report* 85-560: 54p.

Costa, J.; Schuster, R.L. 1988: The formation and failure of natural dams. *Bulletin of the Geological Society of America 100*: 1054-1068.

Davies, T. R. (in prep): Long-term management planning on an active alluvial fan: Waiho river fan, Westland, New Zealand.

Finlayson, B; Statham, I. 1980: *Hillslope Analysis*. Butterworths, London, 230p.

Griffiths, G.A.; McSaveney, M.J. 1983: Distribution of mean annual precipitation across some upland regions of New Zealand. *New Zealand Journal of Science 26*: 197-209.

Hoey, T.P. 1990: Aggradation in the Waiho river. Final Report, West Coast Regional Council, 23p.

Hovius,N.; Stark, C.P.; Allen, P.A. in press: Sediment flux from a mountain belt derived by landslide mapping. *Geology*.

Perrin, N.D.; Hancox, G.T 1991: Landslide-dammed lakes in New Zealand - preliminary studies on their distribution, causes and effects. *In*: *Landslides*, Ed. D.H.Bell, A.A. Balkema, Rotterdam: 1457-1466.

Riley, P.B; Meredith, A.S.; Lilley, P.B. 1993: Tunawaea landslide dam collapse - physical and environmental consequences. Proceedings, IPENZ Annual Conference: 629-639.

Scott, B.K. 1996: Dambreak flood hazard from the Callery river, Westland. BE(Nat Res) Final Year Project Report, Dept of Natural Resources Engineering, Lincoln University: 30p.

Singh, V.P. 1996: *Dam Breach Modelling Technology*. Water and Science Technology Library 17, Kluwer, London, 242p.

Thompson, S.M. 1991: SH6: Waiho bridge waterway requirements. Report No CR91.01, Hydrology Centre, Christchurch, New Zealand: 11p + App.

Webby, M.G.; Jennings, D.N. 1994: Analysis of dam break flood caused by failure of Tunawaea landslide dam. Proceedings, I.E. Aust. Conference on Hydraulics in Civil Engineering, Brisbane, Australia: 163-168.