Bedload sediment flux and flood risk management in New Zealand

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Abstract
Flood risk assessment in New Zealand largely ignores the effects on river flooding of geological events such as landslides, eruptions, erosion and earthquakes that are capable of drastically altering bedload sediment flux. Floods occurring wholly or partly as a result of these events have much the same probabilities of occurrence as commonly-used design floods (~ 1% aep) but their consequences are liable to be much greater, because of the alterations they cause to long-term river morphology and behaviour. Flood risk in New Zealand is therefore underestimated at present.

Introduction
Flood risk management in New Zealand is receiving substantial attention today, particularly in the context of the effect of climate change on flood risks (Ministry for the Environment, 2010; Standards Association of New Zealand, 2008). However the processes used for estimating flood risks, as the basis for flood management, are similar to those developed in much less geologically-active landscapes; they fail to consider the effects on flood risks of geological phenomena such as erosion, eruptions, landslides and earthquakes. Herein we advocate a broader approach to flood risks, based on understanding of how New Zealand rivers respond not only to climatically-driven inputs (water), but also to geologically-driven inputs (sediments) and the movement (flux) of these sediment quantities through the river system. The latter are usually ignored, because flood risk analysis has traditionally been the responsibility of hydrologists and engineers, not geologists, and because measuring sediment flux, particularly the bedload flux that causes alterations to river morphology (Davies, 1987), is notoriously difficult.

Following an outline of conventional methods for estimating flood risk, we consider how floods can be affected by processes in addition to heavy rainfall and/or snowmelt. This leads to a recognition that “flood risk” needs to include such occurrences as large landslides drastically altering river behaviour and a river altering its course through the landscape, either incrementally or catastrophically. We demonstrate that the probabilities of such events in the tectonically-active landscapes of New Zealand are of the same order of magnitude as the rainfall-generated flood risks which are conventionally “managed”; but that their consequences are usually much more severe, so that the overall risk from geological events is greater. Thus conventional methods in fact deal only with numerically smaller risks, which is irrational both logically and economically.
Conventional flood risk analysis
In the conventional view a river is a channel through which water flows from its source in the mountains to the sea. When excess rain causes the channel to become over-full, water spills out of the channel onto the adjacent land causing flooding, to an extent correlated with the amount of excess rain. While this is correct as far as it goes, it is not a sufficiently complete view to allow flood risks to be realistically estimated. It implies a number of assumptions:

1. Rivers do not alter their cross-section, planform shape or position (elevation, location) in the landscape; or, if they show signs of doing this, they can be prevented from so doing by engineering.
2. The geometry of a river can be permanently altered by engineering so that it is more convenient for society.
3. The water level at a cross-section in a river depends only on the flow rate of water passing that section.
4. The transport of sediment by the river has only second-order effects on its behaviour.

Some of these are acknowledged to be false, as for instance when a cross-section used for flow estimation has to be re-calibrated because the section shape (usually bed level) has altered, but this knowledge usually does not carry through to the estimation of water surface level corresponding to a given future flow rate.

Flood risk estimation consists of using recorded (usually daily) data on water surface levels at a specific location in a river, and transforming these to flow rates using an empirical relationship between water surface level and flow rate (a “rating curve”). This flow series is then subject to statistical analysis, yielding annual exceedence probabilities for the range of flows recorded. These probabilities are projected into the future for the time corresponding to the design life of whatever facility is thought to be at risk of flooding, and reconverted into water surface elevations. The total damage (probability multiplied by consequence) that will be done to the facility by the water surface elevations of future floods is calculated on a statistical basis (assuming that every 100 years there will be the statistically-expected number of floods of various probabilities; i.e., ten floods of 10% annual exceedence probability (aep), 2/3 of a 1% aep flood, one-tenth of a 0.1% aep flood, …). The effects of climate change (for example) are then estimated by using estimated alterations in rainfall to increase or decrease the flow rates corresponding to different aeps. This procedure is internally rational, of long standing, and accepted practice. Serious issues arise when it is used for decision-making based on cost-benefit analyses (e.g., Davies, 1984), but, although these issues cast doubt on the entire rationale, we are not concerned with them here.

The procedure outlined above assumes that all floods are caused by rain (and/or snowmelt), and that floods result only from water flowing over the banks of rivers onto adjacent land and affecting the use of that land. These assumptions are generally true for many minor floods in New Zealand, and for major floods in less geologically-active places like UK, parts of the USA and Europe, where the procedure was developed. Many floods in New Zealand and other active landscapes, however, have additional causes and additional effects that are not included in the conventional risk analysis and can seriously affect its utility. In particular, the role of bedload sediment flux in altering river morphology and behaviour is significant in generating risks to societal assets located on temporary sediment storage areas – which is where society prefers to locate them. This issue has been addressed by Jakob and Jordan (2001) from a Canadian perspective; we now treat it on the basis of New Zealand experience.
Floods in active landscapes

In geologically-active landscapes, processes other than water flow contribute significantly to flooding. While in most cases heavy rain is a factor (flooding of any sort by definition requires water in substantial quantities), in some it is not, and in many it is not the crucial factor.

The basis of a fuller understanding of flood risk is that the location, shape and behaviour of a river in a landscape are not arbitrary or random (or permanent); they result from the intrinsic behaviour of the river in response to the rates at which water and sediment are supplied to it (and, of course, constrained by the non-fluvial features of the landscape it flows through). The water supply rate depends on rate of rainfall in the catchment; the sediment supply rate depends on the rate of erosion in the catchment. Thus, if water and/or sediment supply rates alter, the river will alter its behaviour accordingly (e.g., Lane, 1955). So far so good – water supply rates are a factor in flooding, and if water supply rates alter due to climate change the river will flood differently. Crucially, however, it is also evident that sediment supply rates (and in particular bedload supply rates) are a factor in river behaviour, and can therefore affect flood risks. Here we note that vegetation change, due perhaps to climate change, can cause short- to medium-term alterations in sediment supply that can also feed into river behaviour.

River behaviour does not refer only to alterations in flow rates; it also means changes in the width of the river, or the radii of its bends, or its slope, or its bed elevation, or the number of channels (if it is braided), or its location, or the rate at which it changes its location in the landscape; all of which occur in response to bedload sediment erosion, transport and deposition. It may be argued that river engineering can prevent all these behavioural changes, and keep the river in the state to which people have become accustomed; however it has recently been demonstrated (Davies and McSaveney, 2006) that such engineering is only sustainable in bedload-dominated rivers if continuous artificial removal of sediment from the modified river is carried out *ad infinitum*. This is because the river adapts its form and behaviour so that it can deliver sediment to the sea at the rate sediment is supplied to it from its headwaters; and, in addition, in its natural state a fully-alluvial bedload-dominated river has the characteristics and behaviour that allow the water flow to transport sediment at the maximum possible rate, consistent with constraints on its behaviour such as bedrock gorges. This means that direct artificial alteration of the river or its behaviour causes the sediment transport capability of the river to reduce. Since river engineering does not affect the geologically-determined sediment supply from upstream, long-term sediment supply exceeds the transport capacity and aggradation occurs in the modified reach, requiring sediment removal. The only exception to this is if the river form and behaviour are drastically altered so that, for example, a braided river changes to a single-thread river; however in New Zealand the land being protected from flooding is normally insufficiently valuable to justify the engineering investment required for such drastic management (Davies and McSaveney, 2006).

Can the sediment supply to the river be reduced by catchment management? In all but the short-term the answer is emphatically NO. Erosion is a geological phenomenon, driven by tectonic uplift, weathering and base-level alteration; catchment management can certainly reduce it temporarily, but eventually the geological rate at which sediment is generated must be matched by erosion, and any period of artificially low erosion is therefore followed by more intense erosion to restore the long-term average. The consequent temporary nature of
erosion control works has been demonstrated quantitatively by Davies and Hall (1992).

As an example, consider “accelerated” erosion of deforested hill country under an unaltered climate. Under their original forest cover, hillslopes evolved to a dynamic equilibrium whereby soil was eroded by slips at the same rate it was created by weathering (and perhaps uplift). The maximum soil depth that developed under forest (before a rainstorm was able to cause it to slip) depended on the slope gradient, forest root structure and weathering rate. After forest clearance and establishment of pasture, the soil eroded rapidly (in the absence of forest roots) to reach a new, much lower, maximum depth corresponding to the root properties of grasses and shrubs; but once that new maximum depth was reached, the erosion rate again matched the weathering rate (which admittedly, might be different to that under forest) and/or the uplift rate (which is not affected by vegetation). How long this adjustment might take is unknown and is not important (but it will be shorter in an active than in a less-active landscape) – the point is that long-term (i.e., “sustainable”) reduction of erosion is an unattainable objective. Reforesting cleared slopes will lead to a period (years, decades or perhaps centuries) of reduced erosion while soil depth builds up after tree root development, but eventually the erosion rate will again match weathering. Under forest the erosion events will be larger and less frequent than under pasture, and vice-versa, but the long-term rates will be the same.

From the above it is evident that rivers are affected by alterations in sediment input rate, and behave differently as a result. This applies also to occasional large sediment input rates that occur as part of natural variability in the absence of climate change; every now and then, in a geologically-active landscape, a large landslide (for example) will occur and inject a large volume of sediment into a river. Note, however, that that this large event is a perfectly normal part of the full spectrum of events to which the landscape has responded over the past millennia. This will have a number of effects – the bed will aggrade, overbank flows (floods) will occur in unusually small flows, the river may erode its banks rapidly, or it may alter its course suddenly (e.g., Hancox et al., 2005). Even far downstream these effects will occur, albeit less dramatically and more slowly, but there they will still be serious because most people live in the lower reaches of river valleys. This is our major point; even in the absence of climate change, the natural variability of geological processes can cause dramatic alterations in the ability of a given rainstorm to cause flooding. The risks posed by these processes are, however, completely ignored in conventional flood risk analysis. How important is this omission?

**Landslides**

Evidence is accumulating from the characteristics of magnitude-frequency relationships to show that, in active landscapes, large landslides are the major source of sediment input to river systems (e.g., Malamud et al., 2004; Korup and Clogue, 2009). It follows from this that the behaviour of rivers is significantly affected by these major sediment inputs, perhaps to the extent that, especially in the long term (i.e., decade-to-century timescales), one should consider rivers to be permanently in a state of recovery from the most recent major sediment input (Davies and Korup, 2007). There is recent evidence of the drastic effect of major landslides on river systems (Fig. 1; Hancox et al., 2005) and of their potential impacts on society (e.g., Davies, 2002). This is a novel and unconventional viewpoint; very little mainstream research on river behaviour and management acknowledges that the internal dynamics of rivers may be dominated by external inputs. Nevertheless, it appears to be realistic.
Frequency of geological effects; how important are they?

In many landscapes, geological processes act slowly and their effects on flood risks may be small in comparison with the effects of meteorological processes. This is not necessarily the case in New Zealand, which has one of the most geologically-active landscapes on Earth. The following examples lend quantitative justification to this point.

Earthquakes

The Alpine fault

An earthquake of magnitude 8 on the Alpine fault in Westland has an annual occurrence probability of about 1% at present (Rhoades and Van Dissen, 2003). The probability will increase as time goes by. This event is expected to cause large-scale landsliding in the Southern Alps, on both sides of the main divide. There is solid evidence that the Alpine fault earthquake in 1620 AD was followed by aggradation of several metres depth over much of the ~100 km² Whataroa alluvial fan in Westland (Berryman et al., 2001), and also on the Waiho outwash surface at Franz Josef (Davies and Korup, 2007). These geologically-driven events would have caused widespread river-induced devastation to roads, towns, tourism and agriculture had there been a society like that of the present in place at the time. Large-scale avulsions of the Waimakariri and North Ashburton rivers occurred at about the same time, and may reflect similar effects east of the main divide. The effects of these events are far more catastrophic than those of a ("normal 100-year") 1% aep flood, but have much the same probability of occurrence; therefore the risk they pose to society is very much greater than that of a 1% aep rainfall flood. But conventional flood risk analysis ignores them.

The Greendale fault

An additional risk highlighted by the M = 7.1 Darfield earthquake on 4 September 2010 is that of damage to river control structures. In the 2010 event the stopbanks that reduce flood risk to Christchurch from the Waimakariri River were severely damaged by ground shaking (Environment Canterbury, 2010). Had a major flood occurred while the banks were damaged, the consequences could have been substantial. Further earthquake-induced flooding was caused by downthrow of one meander bend of the Hororata River, Canterbury, by about a metre (Quigley et al., 2010); this caused the river to flow into the adjacent Selwyn River in a new course across farmland. Local farmers spent large sums in deepening the reach below the meander bend to restore the river to its former course.
The Porters Pass fault

We use Christchurch to illustrate the potential impact of a major earthquake; the Porters Pass–Amberley fault zone runs across the Waimakariri River in the lower part of its mountain gorge section, so there is a significant possibility that a rupture on this fault (recurrence interval ~ 1500 years; last rupture ~ 500 BP; $M_W \approx 6.5$; Howard et al., 2005) could cause a major landslide into the gorge, forming a landslide dam. The failure of such a dam has been recognised as a flood risk to Christchurch (Canterbury Regional Council, 1991), since it would generate a high flood in the river. Because the volume of water stored in the temporary reservoir would be small compared to that in a conventional rainstorm flood, however, the peak flow rate would attenuate rapidly as it moved downstream. Of less urgency but greater consequence, and more difficult to manage, would be the subsequent flux of the dam sediment down the Waimakariri. Because the river is incised into its outwash surface, the dam sediment would be reworked down the system fairly rapidly, so that within a decade serious aggradation of the river bed could be starting in the stopbanked reach downstream of Halkett, and working its way towards Christchurch. Although this would not be a sudden-onset crisis, the only realistic way to counter it would be the removal of the excess sediment (possibly tens of millions of cubic metres) from the river bed as it built up – a very significant flood-related cost to the area.

Aseismic landsliding

Since 1991 there have been six very large landslides (~ 10 million cubic metres) in the Southern Alps, none of which was triggered by any identifiable event. Two of these (Mt Adams, 1999; Young River, 2008) blocked rivers, forming landslide-dammed lakes; the Mt Adams landslide dam soon failed, making its sediment available for transport downstream. This drastically altered the behaviour of the Poerua River, causing severe damage to a large farm and revealing the potential for severe flooding as a result of a major sediment input (Davies and Korup, 2007). The Young River landslide dam has not yet failed. Landslide magnitude-frequency data allow the annual probability of a landslide forming a dam of the size in the Poerua in 1999 to be calculated; it is about $1.5 \times 10^{-3}$ (Davies, 2002). While this is not high, neither is it negligible, and nor are the potential risks of such events occurring where they can do much more damage. For example, a comparable event in the Callery Gorge 30 km farther south would devastate the burgeoning tourist township of Franz Josef Glacier, and has an annual probability of 1–2% (Davies, 2002). Under unfavourable circumstances (e.g., a landslide occurring late in the evening of a heavy rainstorm), it could occur with no warning, causing a substantial death toll. Even with no deaths, the subsequent sediment flux would cause severe aggradation affecting Franz Josef and the state highway, which would in turn profoundly affect the economy of Westland.

Debris flows

On a smaller scale, the hazard of debris flows (many if not all of which originate as landslides) is for the present well appreciated in New Zealand as a result of the 2005 Matata event, in which a new subdivision built on a debris-flow fan was destroyed by a debris flow (McSaveney et al., 2005). The event was completely unanticipated, although in retrospect it has become clear that plenty of evidence was available that similar events had occurred on the same site in the past. Such events threaten life and infrastructure in a way that “normal” floods do not; again, this is because they involve substantial quantities of sediment. Their hazards cannot be managed on the basis of conventional flood frequency methods (Davies and McSaveney, 2008; Davies, 1997).
New Zealand has had few debris-flow catastrophes to date, probably due to relatively sparse development. In Japan, which has a similar geoclimatic environment but is at least an order of magnitude more densely populated, several tens of deaths are caused by debris flows every year. The implication is clear: as development in New Zealand becomes more extensive, debris-flow disasters will become more frequent. Certainly, small-scale landsliding, which is often accompanied by debris flows, is recognised as one of New Zealand’s most costly hazards; however its potential impacts on flood risk are rarely considered.

Volcanic eruptions
The active volcanoes of North Island, New Zealand, pose well-known hazards in the region; these include lahars, pyroclastic flows and sector collapses. The effects of major events such as lake breakouts on river floods have been considered (e.g., Hodgson and Nairn, 2005). However, the flood risk due to extensive ashfall in river catchments has apparently had little if any attention in New Zealand (and indeed worldwide; Favalli et al., 2006). Severe rainstorms following eruptions that yield copious volcanic ash could see very large increases of sediment input to rivers, with corresponding effects on river behaviour and flooding. While the probability of a severe ashfall is difficult to estimate, Stirling and Wilson (2002) show that Taupo volcano is expected to generate $10^8$ m$^3$ of ash with a 0.2% annual probability. This shows that the ashfall-generated flood hazard is not negligible; 0.2% is the same annual probability as that used for the design of structures against damage due to natural processes – including floods (Buildings Act, 2004; AS/NZS 1170.0:2002).

Where to from here?
We have pointed out what we perceive to be significant shortcomings in flood risk assessment procedures in New Zealand. From this it appears that investment in procedures to manage flood risk may be misdirected; we have taken as an example the substantial investments presently being made into investigating the effects of climate change on flood risk, which may well turn out to be smaller than the inaccuracy in the present estimations of flood risk. What, however, is the alternative?

In 2008, NZS 9401:2008 “Managing Flood Risk – a Process Standard” was issued (Standards Association of New Zealand, 2008). This applied the methods of the Australia/New Zealand Risk Management standard AS/NZS 4360:2004 to the physical, social and economic context of flood risks and their management. It explicitly addresses five elements of flood risk:

1. the natural framework of the catchment from which floods are generated;
2. the need to consider natural and social systems together so that management of both is sustainable;
3. adaptive management strategies that accept the unpredictability of natural system behaviour, and emphasise the need for society’s willingness to adapt to nature;
4. risk management to include wide appreciation of types of risk and types of response; and
5. comprehensive risk treatment strategies, including reduction, readiness, response and recovery.

This is clearly very much in line with the view of flood risk set out herein – in other words, the essence of our message has already been adopted at a fairly high level, albeit in a non-binding document.

NZS 9401:2008 also recommends a case-by-case treatment of flood risk situations, accepting that given the wide range of flood-generating processes (both natural and anthropogenic), each situation will
be different. This implies that a common approach, such as the conventional return-period/cost-benefit analysis framework, is unlikely to produce optimal solutions to many flood problems. To date, however, there is little indication that hard-pressed councils and consultants have the opportunity or resources to work on the detailed guidelines that need to be developed beneath the high-level principles of the Standard.

We suggest that implementation of the Standard in decision-making for flood risk management is a crucial step towards recognising and incorporating geological influences on flood risk. This clearly needs resourcing. It seems logical to suggest that some of the funding presently devoted to detailed assessment of climate-change-induced alterations to flood risk might sensibly be devoted to the demonstrably more urgent task of developing operational procedures for comprehensive flood risk assessment.

Conclusions

Conventional flood risk analysis methods developed in less geologically-active landscapes are inadequate for quantifying flood risk in New Zealand. At best, an incomplete representation of New Zealand flood risk is able to be developed. To develop a more realistic representation of flood risk, the ability of geological processes (erosion, eruptions, earthquakes, landslides, debris flows) to put lives and infrastructure at risk by affecting river behaviour must be considered routinely. At present this does not occur.

The risks that are being ignored in conventional flood risk analysis have similar probabilities to those that are taken into consideration. However, because the alterations to river behaviour that they can cause are much greater than, and very different from, those of conventional floods, their consequences will almost certainly be very much greater, so in fact the risks that are commonly being considered are numerically smaller than those that are being ignored. This is clearly irrational and will inevitably have severe economic consequences as unexpected sediment-affected floods occur in future.

The effects of climate change on flood risk may be negligible compared with the underestimations of flood risk intrinsic in current assessment methods; before detailed work on climate-change-induced flood risks can be useful, fundamental improvements are needed to procedures for assessing flood risks in New Zealand. This work needs to begin immediately.

References


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