Institute of GEOLOGICAL & NUCLEAR SCIENCES Limited

Confidential

The 18 May 2005 debris flow disaster at Matata: Causes and mitigation suggestions

by M. J. McSaveney, R. D. Beetham & G. S. Leonard

Client Report
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Frontispiece "*Civilisation exists by geological consent, subject to change without notice*." William Durant, 1885–1981. Debris-flow deposits and damage from Awatarariki (top) and Waitepuru (bottom) Streams at Matata.

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Prepared for

Whakatane District Council

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"Civilisation exists by geological consent,
subject to change without notice."
William Durant, 1885–1981.

Natural hazards are an inescapable part of life on planet Earth. We cannot predict or prevent earthquakes, volcanic eruptions, tsunami, landslides, floods or storms. But we can use our collective knowledge to reduce their toll.

Society's vulnerability increases with urban growth and with our increasing dependence on infrastructure. The built environment is less resilient than the natural one, and a damaging earthquake or eruption can debilitate communities for years.

Reducing Society's vulnerability to natural hazards is the best way to save lives and protect our economy.

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EXECUTIVE SUMMARY

On 18 May 2005, a band of intense rain passed over the catchments behind Matata. It triggered many landslips, and several large debris flows, which, with their associated flooding, destroyed 27 homes and damaged a further 87 properties in Matata. SH2 and the railway were closed for many days. The rainfall appears to be not more than a 500-year recurrence event (about 10% probability in 50 years), and it is convenient to treat the associated debris flows as having a similar recurrence interval. There is evidence that equally as large, and larger debris flows have occurred many times since 7000 years ago. Historical records indicate that probably four smaller debris-flows have occurred since 1860.

Witness descriptions and physical evidence indicate that debris flows caused the damage to Matata in the vicinity of Awatarariki and Waitepuru Streams. Debris flows are classified by experts as a type of landslide. They are dense fluid mixtures of all manner of rock, soil, organic debris and water which move rapidly, and are capable of carrying immense boulders. Boulders up to 7 metres across were moved by Awatarariki Stream's debris flow. Evidence in the stream headwaters indicates that the primary causative events that inevitably led to the debris-flow damage at Matata were landslips of the type termed *debris avalanches,* triggered by exceptionally heavy rain. The debris flows directly damaged some homes and property. Other homes and property were damaged by debris floods that extended beyond the debris flows. A debris flow is usually accompanied by a debris flood, which is regarded by experts as an integral part of the total debris-flow event.

We also determined from physical evidence that:

- A debris flood damaged property in the vicinity of Waimea Stream. We could not determine whether this debris flood had an associated debris flow. A debris flood is less damaging than a debris flow, and can occur in the absence of a debris flow.
- A debris flood damaged homes and property in the vicinity of Awakaponga Stream. It was a direct consequence of a debris flow that caused no direct damage.
- In the vicinity of Ohinekoao Stream, a debris flow reached to SH2. Its associated debris flood damaged the railway and property beyond.
- The landslides directly from the hillsides above Matata, and beside SH2 to the west, were debris avalanches. These are similar to debris flows, but lack a confining channel. Similar landslides falling into catchments south of Matata initiated the debris flows.
- Landslides that fell ***after*** the first debris flows had passed are the only evidence for debris dams in the streams. The highly erosive debris flows cleaned out the valley bottoms, and destabilised slopes along the channel, causing secondary landslides.

The boulders carried by the debris flows came mostly from boulders that were buried in the stream beds and banks. They got there by falling from the bluffs above the stream at various times in the past. Most of the harder boulders are derived from strongly welded ignimbrite of the Matahina formation. The boulders eroded from the channels already are being replaced by collapse of the steep slopes, a continuing process. The supplies of boulders in the channels were depleted, but not exhausted on 18 May. Further debris flows are possible whenever there is rain with high enough intensity to trigger landslides on the steep slopes.

The earthquake swarm that has been shaking Matata for many months did not contribute to the disaster. Landslips that occurred in the far stronger 1987 Edgecumbe earthquake were the source of some of the boulders that were carried by the debris flows. Others fell in landslips on 18 May, but many were already in the bed and banks of the channel from earlier events, and were picked up by the immensely erosive debris flows.

Debris flows are more dangerous than floods. For two reasons they make the flooding associated with them much worse than it would be without a debris flow: (1) they travel faster than the flow of water in the same channel and pick up all of the floodwater in their path, thus delivering water to the catchment outlet faster than would be possible in a simple flood; (2) deposition of sediment from a debris flow can fill the normal stream channel and allow the draining water to flood into areas not normally accessible by floodwater.

Hyperconcentrated flows of sediment-laden water draining from the debris flows caused debris floods; water so highly charged with sand and silt that it no longer behaved like normal water; it flowed faster and was more dense, and was capable of moving larger boulders than could be moved by a normal flood flow across the lowland fans at Matata.

The landslips that initiated the debris flows were triggered by intense rain, probably in excess of 2 mm/minute which fell during a severe thunderstorm. This intense rainfall fell in a narrow band only a few kilometres wide that passed across the catchments to the south of Matata from near the mouth of Ohinekoao Stream to Awakaponga. Had this band of rain been some 500 m closer to Matata, a different, and much more devastating outcome might have occurred. The existing debris flows could have been larger, and other catchments also could have poured debris flows into Matata. In addition, there may have been more debris avalanches from the slopes immediately behind Matata. Such events have happened many times in the prehistoric past, creating the land on which Matata stands.

Parts of Matata are naturally protected from flooding and debris flows, because the ancient debris flows fans were trimmed by Tarawera River, and the streams draining from the upper catchments now are cut deeply into the toes of the fans, leaving much of the land free from flood risk. The low railway embankment gives some other parts of Matata varying degrees of protection from water and debris floods, by diverting shallow flows. The railway also increases the danger to some areas, because it diverts flows to areas not otherwise at risk.

There are areas around Matata that are unsafe for habitation. Significant areas of present-day Matata have always been at risk from debris flows, debris floods and debris avalanches. These are wider than the currently affected areas. With engineering works, it is possible to reduce the danger to some areas to commonly accepted levels, but there are other areas where such mitigation probably is not feasible. Here, it will be necessary either to accept the risk, or remove dwellings. Of course, areas designated as floodways or debris-flow routes will be uninhabitable, but could be used for recreation.

Accepting the risk need not endanger lives. Weather radar sited in the Bay of Plenty area could provide effective early warning of high-intensity rain storms for the greater Bay of Plenty region and significantly improve existing weather forecasting of severe storms.

Effective engineering mitigation of the hazards to Matata requires integrating such protection with works associated with the railway and SH2. Of critical concern are bridges and culverts; where these are too small or misaligned, they obstruct flow, causing deposition and a somewhat random choice of path for flows that follow. For effective works, the debris path must be predictable and controlled, otherwise, restricting building is the only safe option.

We recommend that:

- Communities in the wider Bay of Plenty area explore the potential of having a locally based, weather-radar system for warning of severe storms.
- The Matata community pays attention to the danger of small steep streams, and allocates adequate space for them to pass safely through Matata.
- The community at Matata consider the feasibility of having debris-flow detention basins on Waitepuru and Awatarariki Streams.
- A bund be constructed on the Matata side of Awatarariki Stream to divert debris floods.
- Waitepuru Stream be diverted to a course that bypasses Matata – to reduce stream channel siltation and improve the safety from flooding.
- Residents adjacent to Waimea Stream be told that there is a danger from debris flows, but we do not know if debris-flow mitigation work is warranted.
- The hazard from inundation by hyperconcentrated flows from Waimea Stream be mitigated with an adequately designed railway culvert, and erosion-resistant channel downstream.
- Residents of properties landward of the railway between Simpson and Clarke Streets on Pakeha Road, be told of the risks of inundation and landslides at those sites. Consider possible mitigation options for these sites to reduce the risk.
- Realignment and redesign of the SH2 and railway bridges at Ohinekoao Stream if property on the seaward side of the railway is to be protected from debris flows and floods from the stream.
- A combined approach between the authorities controlling the railway, SH2 and the Matata community to provide overall effective flood and debris-flow mitigation works.
- The boulder bund at Awakaponga Stream be extended a little further, and covered with soil. We commend the initiative already taken there.
- Further, less robust bunds lower on the fan of Awakaponga Stream be considered to adequately protect property and dwellings there.

1.0 INTRODUCTION

On 18 May 2005, at the end of a day of moderately heavy rain (153 mm in 17.75 hrs at Awakaponga), a band of intense rain (130 mm in 1.75 hrs) passed over the catchments behind the coastal settlement of Matata. It left in its wake 27 destroyed homes and 87 damaged properties in Matata. SH2 was closed for 12 days, and the railway, for more than 20 days. It did all this by triggering many landslips, major debris flows and severe floods in Ohinekoao, Awatarariki, Waimea, Waitepuru, and Awakaponga Streams. Although many homes, and much property were destroyed, there were no serious injuries or deaths.

Debris flows are unfamiliar to the New Zealand public, and to many of New Zealand's natural-hazard specialists. As a result, when debris flows occur, people generally call them "floods", or "flash floods". It is useful to distinguish between floods and debris flows, because the behaviour of a debris flow is very different from that of a conventional flood of dirty water. For the same amount of rain, a debris flow has a much higher discharge than a flood, it contains more and often larger rock debris, and it moves faster. As a consequence debris flows are far more dangerous and more difficult to deal with than floodwater.

In a conventional flood there is much more water than sediment; the huge mass of rushing water carries fine sediment suspended in it, and coarse sediment is dragged along by the rush of water. The bulk of the sediment moves more slowly than the bulk of the water. In a debris flow, there is strong interaction between the water and the sediment, and the fast-moving sediment carries the water along with it, faster than either would move in a conventional flood. Debris flows do not occur in large rivers, and generally are restricted to small, steep streams. In streams that can host them, debris flows tend to be much larger, and far more destructive than any flood in the same stream. One of the reasons for this is that above some threshold of flood size in susceptible catchments, floods tend to transform into debris flows if there is enough sediment available around the stream channel. In eroding the bed and banks, the volume of the flow bulks up to be many times the volume of water alone. One way in which a large enough flood can be created is for water to pond behind a landslide dam in the channel, and the breakout surge of flood water as the dam breaches sometimes is sufficient to initiate a debris flow. Debris flows also can initiate in other ways; when the rainfall intensity is high enough, the natural subsurface drainage system is overwhelmed. The pore-water pressure in the slope then increases rapidly and causes landslips, which cascade from steep slopes into the stream channel, picking up more rock, soil, and trees on the way. In their fall to the channel, the landslips can become so fluid that they do not stop at the foot of the slope, but continue down the channel, picking up more debris along their path — they have now formed a debris flow. This was the mechanism that operated widely on 18 May in the catchments behind Matata. There are other ways that debris flows can form, but we need not be concerned with those here.

Debris flows were the primary hazard at Matata on 18 May 2005, but they were accompanied by flooding too (Figure 1.0.1). Debris flows do not usually occur without associated flooding downstream. The debris-flow hazard at Matata, hitherto, was unrecognised, even though events now recognised as debris flows have occurred a number of times within the collective memory of the people of Matata. Because debris flows are one of the more destructive natural hazards, now that the hazard is recognised, there is need for the people of Matata to consider ways to reduce the danger. A range of debris-flow mitigation measures is available. They include a variety of engineering works to halt or deflect debris flows, and a range of land-use options. The important thing is to not have people and homes in the way of future debris flows. The people of Matata were very fortunate on 18 May that no one was killed; debris flows are usually lethal.

Figure 1.0.1 A landslide of the type known as a debris flow was the primary hazard at Awatarariki Stream on 18 May, but it was accompanied by flooding too. The boulder-laden debris flow destroyed the rail bridge and houses, then debris-laden water draining from it damaged further houses and property, and filled the lagoon. Photo by Bernard Hegan.

1.1 Purpose and scope of the report

This report is on the natural processes leading to, and consequent on, the debris flows at Matata. It has been prepared by Dr Mauri McSaveney, Mr Dick Beetham and Dr Graham Leonard of the Institute of Geological & Nuclear Sciences (GNS), for the Matata Recovery Project of the Whakatane District Council. Dr McSaveney has studied a number of debris flows, and recently has contributed to an international state-of-the-art text on debris-flow hazards and their mitigation[2]. Mr Beetham is an engineering geologist and civil engineer. He has broad experience in the assessment of earthquake and landslide disasters and is a Fellow of the Institute of Professional Engineers of New Zealand. Dr Leonard is a geological mapping specialist with expertise in volcanology. He currently is revising the 1:250,000 scale geological map of this part of New Zealand.

The report's objective is to present an analysis of the geological and runoff processes during the extremely intense rain of the 18-May 2005 storm in the Matata catchments (Ohinekoao, Awatarariki, Waimea, Waitepuru and Awakaponga Streams), and to assess likely future risks and their consequences to Matata. The purpose is to provide Whakatane District Council and the people of Matata with background to enable informed decisions on hazard-mitigation options, and future land use around Matata.

The report presents:

- the results of analyses and investigations of the 2005 debris flows and the consequent floods based on the authors' site visits on 23–25 May and 9–10 June, 2005, and discussions with others;
- scenarios for future events with likely debris flows and their extent on the Matata coastal plain;
- possible mitigation measures.

Dr McSaveney and Mr Beetham inspected damage at Matata on 23–25 May as part of the GeoNet landslides rapid response supported by the Earthquake Commission. On 25 May, they flew by helicopter at low altitude over the headwaters of Awatarariki and Waitepuru Streams. On 9–10 June, Dr McSaveney, Mr Beetham and Dr Leonard walked short distances up the channels of Ohinekoao, Awatarariki, Waimea, Waitepuru and Awakaponga Streams. We have examined vertical aerial photographs taken in 1944, 1960, 30 May 2005, oblique aerial photographs taken in early June 2005 by Graham Hancox of GNS, and a number of reports listed in Section10.0.

1.2 The Brief

This report has been prepared for Whakatane District Council in accordance with a brief determined by Mr Tom Bassett of Tonkin & Taylor Ltd. and others in consultation with Dr McSaveney and Mr Beetham. The brief is as follows:

Brief:	G: Catchment Processes
Issued to:	IGNS, P O Box 30368, Lower Hutt
Objective:	To provide an analysis of the geological and runoff processes in the catchments under extreme rainfall conditions experienced during the 18 May 2005 storm event in the Matata catchments, and assess likely future risk and consequences.

Scope of Services:

1. To identify the cause or causes of the disaster at Matata (landslip/flood or both).
2. To assess the main catchments (Ohinekoao, Awatarariki, Waimea, Waitepuru, Awakaponga) and the slopes behind and above the town, railway and state highway, in terms of the recent event and the likely processes that contributed to the damage, including:
   a.) Catchment geology and geomorphology and their effects on headwater slope stability;
   b.) Land cover and effect of vegetation on stability and erosion potential;
   c.) Recent seismic activity and its effect on stability and erosion potential;
   d.) Sediment transport processes active during the storm event;
   e.) Possible damming of debris in streams;
   f.) Channel erosion.
3. To estimate quantity of solid material and debris delivered from catchments in the May 18 event.
4. To comment on likely catchment response to hydrological events in:
   - The immediate term, in relation to silt in the catchments and recently deposited in the channels, and its vulnerability to movement downstream in rainfall and associated runoff events expected at least several times a year;
   - The short term (up to ten years), i.e. significant but relatively common events;
   - The long term (up to 1,000 years), i.e. extreme but low probability events.

5. To delineate area of risk from debris-flow (lahar) and debris-flood deposition downstream of catchment outlets upstream of the town
6. To identify possible works options to mitigate risk and minimise the affected area in future events.

Deliverables: A report setting out:

- the results of the analyses and investigations of the 2005 event
- scenarios for future events with likely debris flows and extent on Matata coastal plain
- possible mitigation measures

Liaison: EBoP for hydrological and survey information
T&T regarding geological issues, progress and project management

Delivery: 24 June 2005

1.3 Terminology Used

Although *debris flows* and *debris avalanches* are unfamiliar to the New Zealand public and to many natural hazard specialists, they have long been included in widely used landslide classifications as technical terms for a particular type of landslide. For example the authoritative landslide reference texts *Landslides - Analysis and Control, Special Report 176, Transportation Research Board, National Research Council, National Academy of Sciences, Washington DC, 1978,* edited by Robert L Schuster & Raymond J Krizek and its updated edition *Landslides: Investigation and Mitigation, Special Report 247, Transportation Research Board, National Academy Press, Washington DC, 1996,* edited by A Keith Turner & Robert L Schuster, both define *debris flows* and *debris avalanches* as types of landslides, giving examples of their occurrence, and their mitigation.

In this report, we follow current internationally accepted landslide terminology recently reviewed by Professor Oldrich Hungr[3]. Some relevant terms are:

- A *debris flow* is a very rapid to extremely rapid (5–10 m/s, 15–30 km/hr) flow of water-saturated, non-plastic (granular) debris in a steep channel. Speeds faster than a fit human can run are common. Besides those at Matata, debris flows have occurred in many New Zealand localities, causing deaths at Blandswood, Te Aroha, Klondyke Corner, Motueka, and the Rees Valley. Huge debris flows occur regularly in the Tien Shan Mountains of Kyrgyzstan during the Spring thaw (Figure 1.3.1).

Figure 1.3.1 Foundations of a farm building destroyed by a debris flow in the Tien Shan Mountains of Kyrgyzstan in 2004. As at Matata, the evidence for past huge debris flows can be read in the landscape, allowing opportunity to avoid such damage though mitigation works and appropriate building restriction where necessary.

- A *debris flood* is a very rapid (up to ~5 m/s), surging flow of water, heavily charged with debris, in a steep channel. A damaging debris flood occurred recently at Paekakariki, north of Wellington during an intense rain storm in October 2003[4] (Figure 1.3.2), and again in February 2004 and January 2005.

Figure 1.3.2 *Debris-flood* gravel from the gully exit near Paekakariki Hill Road, north of Wellington, as a result of the storm of 3 October 2003 burying the Belvedere Motel and cars (Hancox G T, 2005).

- A *debris avalanche* is a very rapid, to extremely rapid(5—~20 m/s, 15–60 km/hr), shallow flow of partially or fully water-saturated debris on a steep slope, without confinement in an established channel. Several debris avalanches which occurred during the storm from the steep cliffs just northwest of Matata spread water laden soil and tree debris over the road and railway line (Figure 1.3.3).

Figure 1.3.3 *Debris avalanches* from the old seacliff, northwest of Matata, at Herepuru Road. SH2 in the foreground. *Debris avalanches* such as these initiated *debris flows* when they fell into stream channels in catchments behind Matata.

Figure 1.3.4 Several *debris avalanches* within the headwaters of Awatarariki Stream. Many d*ebris avalanches* such as these formed *debris flows* when they reached the stream channels.

- *Debris* in these contexts is loose, unconsolidated material of low plasticity. In texture, debris is a mix of silt, sand, gravel, cobbles and boulders (Figure 1.3.5), often with a trace of clay, but not necessarily so. Debris also may contain a significant proportion of organic material including logs, stumps, and organic mulch (Figure 1.3.6).

Figure 1.3.5 Debris flows are known for their ability to transport huge boulders as part of their mix of water, sand, gravel, cobbles and boulders. This huge boulder of bedded siltstone in the bed of Awatarariki Stream probably fell into a passing debris flow when the valley side a hundred metres or so upstream was undercut by the highly erosive debris flows. It was part of a late-phase debris-flow pulse that stopped in the area of the old quarry. Earlier, larger pulses reached out onto the lowland plain at Matata (as in the Frontispiece).

Figure 1.3.6 Organic debris from the catchment forest cover is estimated to have been perhaps 10% of the total debris carried by the debris flows at Matata.

Professor Hungr uses and recommends use of the term *debris flow* as a long-established keyword for the *entire* phenomenon; from an initiating landslide on a steep slope, the rapid flow along a steep confined channel, and the deposition on a debris fan. There almost always is a debris flood as a continuation downstream of a debris flow, and it is usual to extend the term *debris flow* to include the associated debris flood when referring to the entire event.

The distinction between *debris flow* and *debris avalanche* is useful in hazard studies even though the flow processes are identical in the two, because debris flows follow established channels and deposit primarily on fans, while debris avalanches may potentially affect any steep slope (of course they often enter channels and become debris flows). Debris flows repeat often in the same channel, but debris avalanches seldom repeat on the same portion of slope.

When a debris flood occurs without an associated debris flow, the distinction between debris flow and debris flood is usually easiest made on the basis of peak discharge during an event. Peak discharge during a debris flood is limited to at most 2–3 times that of a major flood as it results in relatively low flow depths (and therefore results in relatively limited damage). On the other hand, debris flows produce extremely large peak discharges by eroding and incorporating sediment from the stream's bed and banks as well as the stream's water as it surges down the channel at a faster speed than the flooded stream can flow. Peak discharges from a debris flow can be as much as 50 times as large as those of a major flood. Their destructive potential is much greater than that of a flood. In the aftermath of a debris flood, many structures are filled with sediment, but suffer little structural damage. This latter feature, however, was not a reliable guide at Matata, because some homes there were structurally damaged by rolling boulders in the debris-flood phase downstream of the debris flow.

A typical debris-flow path can be divided into an initiation zone, a transport and erosion zone, and a deposition zone. Most often, the initiation zone is a slope failure (landslip or slide) in the headwall or side slope of a gully or stream channel. The slope failure may have the character of a shallow debris slide (i.e. sliding rather than flowing), transforming into a debris avalanche (with both sliding and flow). Sometimes, the bed of the channel itself can become unstable during extreme flood discharge, and the debris flow initiates spontaneously in the steep bed of the channel. Generally, the debris-flow initiation zone has a steep slope between 20° to 45° or more. Often the initiating slide is only a few tens of cubic metres in volume, yet it can grow to a major debris flow. Under conditions of extreme rainfall intensities, there may be many shallow slides. Some may coalesce on the hillside to form larger debris avalanches. Also, many smaller debris flows in tributary channels can coalesce to form major debris flows. Such was the case in the catchments south of Matata on 18 May 2005.

Debris flow*s* commonly move in distinct surges or slugs of debris, separated by watery intersurge flows. A debris-flow event may consist of one surge, or many tens of surges. Surging arises for a number of reasons; some surges result from flow instability caused by longitudinal sorting of the debris-flow material. Such surges are characterized by boulder fronts – that are mostly boulders and other large debris (trees). The main body of the surge is a finer mass of liquefied debris, and the tail (or *afterflow*) is a dilute, turbulent flow of sediment-charged water, similar to a debris flood.

The main deposition area of a debris flow commonly occurs on an established fan, usually referred to as a *debris-flow fan*. Deposition occurs because of a combination of slope reduction and a loss of confinement. As a result of the deposition process, debris-flow behaviour varies with distance downstream from the fan apex. On the upper part of the fan, coarse debris forms high discharges and thick deposits. On the lower parts, finer and thinner deposits form, and flow velocities may be reduced. An afterflow of heavily sediment-laden water reaches the margin of the fan and may continue into the stream channel system below, with the character of a debris flood. Many debris-flow deposits on fans are significantly reworked by water flow immediately following a debris-flow event. Because of the often massive deposition at the fan head, the direction of flow of a debris flow on a fan is very unpredictable. Successive pulses of debris flows are readily diverted by the deposits of earlier pulses, and conventional flood protection measures can be overwhelmed.

Another useful term in the context of the debris flows at Matata is *hyperconcentrated flow*[5]. Water floods usually transport mostly fine sediment and in relatively small quantities in proportion to total flow volume, with the suspended sediment having little effect on the flow behaviour. Sediment concentrations are generally less than 4% by volume (10% by weight). At the other end of the spectrum, debris flows may transport more sediment than water, with sediment concentrations often in excess of 60% by volume (80% by weight), and the sediment plays an integral role in the flow behaviour and mechanics. The term *hyperconcentrated flow* is applied to flows intermediate between these end-members. Debris flood*s* as discussed earlier, are large, sediment-rich flow events, which may or may not involve hyperconcentrated flow. Hyperconcentrated flow is a distinct flow process that can occur at low as well as high discharges. A hyperconcentrated flow is a flow of water so highly charged with sand and silt that much of its turbulence is damped out and its flow appears to be smoothed and oily, though it may be moving faster than an equivalent depth of clean water. The normal small-scale surface choppiness and splashes of water are missing on hyperconcentrated flows. A dense, fast-moving hyperconcentrated flow is capable of moving larger boulders along the bed of the flow than is the equivalent normal flow of water. Some witness descriptions of the floodwater at Matata[6] fit hyperconcentrated flow from debris flows, and we saw one small stream west of Matata in hyperconcentrated flow on 23 May when it was far from being in flood (Figure 1.3.7).

Figure 1.3.7 A small stream west of Matata, beside SH2 photographed in hyperconcentrated flow on 23 May. The flow appears to be thick and oily. Much of the surface roughness usually seen on a clear stream is damped out because of the high density of the flow. Witnesses described and photographed[7] hyperconcentrated flows at Matata on 18 May.

1.4 Debris flows and lahars

Some people have called the debris flows at Matata *lahars*. The term *lahar* is used for debris flows and related hyperconcentrated flows and debris floods that occur in volcanic materials on the flanks of a volcano. Geologists recognise that the hills to the south of Matata form the northern flank of what is known as the Okataina volcanic centre, arguably New Zealand's largest and most explosively active volcano. It has been so active through New Zealand's pre-history that today it is well hidden and difficult to recognise beneath its deposits. Much of the rock material in the debris flows at Matata was erupted from various vents of this volcano over the last few hundred thousand years or so. Very little of it is younger than 1800 years, however, and a part of the rock material in the deposits also is not from the volcano, but from underlying sandstone and siltstone beds. Hence, it is stretching the lahar concept to apply it to the events of 18 May in the catchments behind Matata. Had the same meteorological conditions of 18 May hit similar-sized catchments without the volcanic deposits, debris flows still would have been a likely outcome. For these reasons, we prefer to use the term *debris flow*.

1.5 Relevant terms in New Zealand statutes

To put the above terminology into a New Zealand legal context with respect to Matata, we refer to terms used in the Building Act (2004) and the Resource Management Act (1991). The Building Act (2004) does not use the term *debris flow*, or list the deposition of sediment on land as a hazard (as did the previous Building Act of 1991), although the converse of deposition (erosion) still is listed as a natural hazard. The Resource Management Act uses similar terminology to the Building Act (1991) with one exception noted below.

Erosion is the process of removal of land, usually by the action of running water. In the Matata context, this is scour of stream banks, and excavation of a new channel after a stream break-out (= avulsion - see below).

Avulsion is the switching of a stream or individual channel from one course to another (often called a stream *break-out*); the flow may create a new channel or use a previously abandoned one. In the Matata context, this happened at all of the major streams where deposition of sediment caused streams to switch to new channels. Avulsion was a natural hazard under the old 1991 Building Act but it is not now a natural hazard in itself under the Building Act (2004). Avulsion now legally is replaced by two natural hazards, erosion and inundation, in the 2004 Act.

Alluvion is an obscure term used in the 1991 Building Act, but not in the 2004 Act (alluvion is the Spanish word for debris flow). In the context of the 1991 Act, alluvion probably was intended to be the more common technical term *alluviation*, which is sediment deposition both in the stream channel, or on adjacent land. The term *siltation* is synonymous with both alluviation and sediment deposition even though the sediment need not be silt. The Resource Management Act (1991) does not use alluvion, but uses the term *sedimentation* in an identical context to the 1991 Building Act's alluvion. Neither alluvion nor sedimentation are natural hazards under the Building Act (2004). However, alluvion (sedimentation) can not occur without flooding, which is a subset of inundation, which is a natural hazard under the Act.

Falling debris is another natural hazard in the Building Act (2004), and is any rock, soil, snow or ice, (and associated vegetation moving) moving under the influence of gravity from offsite to cause harm at a site. *Falling debris* is not a technical term in general use, but is readily understood by technical experts to include any form of landslide that comes from upslope to cause damage below. The Building Act's falling debris should be viewed as the principal natural hazard covering the Matata debris flows. Falling debris (from other landslide types) also is the hazard to homes at the toes of the slopes south of the railway. Those homes, however, that were not affected directly by the debris flows, but by the debris floods that drained from them, experienced the Building Act's natural hazard of inundation (see below). The distinction is only important because the mitigation measures may be different.

Subsidence is another of the natural hazards in the Building Act (2004), and occurs with ground-water use in some areas, collapse of land over abandoned coal and gold mines, collapse into limestone caverns and areas of geothermal solution, collapse over buried melting ice, and differential compaction when soils liquefy during earthquakes. It is one of the natural hazards excluded from coverage by the Earthquake Commission. It is not a significant hazard on currently developed areas around Matata, but could be an issue if urban development occurred on the infilled lagoons.

Inundation includes flooding, overland flow, storm surge, tidal effects and ponding. Flooding and overland flow can be either from flooded streams, or directly from heavy rain. Under the Building Act (2004) inundation has to be viewed as the natural hazard that also includes avulsion, sedimentation and some aspects of alluvion (and also could include debris-flow inundation). Inundation historically has been a significant hazard around Matata.

Slippage under the Building Act (2004) means landslips (= landslides), but in the context of the land on the site moving offsite (and thereby becoming *falling debris* for another site).

Sedimentation is the both the process of deposition of sediment on land and the sediment itself that remains. Sedimentation is to be considered as a natural hazard under the Resource Management Act (1991) but it is not a natural hazard under the Building Act (2004). This is a curious omission, because erosion, which is the converse of sedimentation, and technically can be considered to be negative sedimentation (and vice versa) is a natural hazard in both Acts. Both can be dangerous and destructive. Sedimentation includes deposition by debris flows.

There is no legal anomaly created if any particular potentially adverse natural event (= natural hazard) might be considered to be any of a variety of legally defined natural hazards under one or more statutes, provided that any measures to be considered are appropriate for the type of physical phenomenon. That is, it does not matter whether one classifies *debris flows* as inundation, sedimentation, or falling debris, providing that the measures taken to avoid damage from debris flows is appropriate for debris flows. Further, there are other real natural hazards, such as earthquakes and strong wind that are not listed as natural hazards under Section 76 of the Building Act (2004), but which must be considered in the design and construction of buildings.

Debris flows are invariably structurally damaging to buildings they impact on, and not merely an inconvenience as inundation by floodwater often is. Hence, debris flows should be considered in the same context as other structurally damaging hazards such as earthquakes and strong wind. Under the codes associated with the Building Act (2004) it is appropriate to adopt standards of construction of dwellings such that they might have a 90% chance of lasting their expected lifetime, usually taken as 50 years. It follows that the appropriate level of protection from debris flows is that of the debris flow of 10% probability in 50 years (which is usually rounded to an event of 500-year return period), whereas for protection from the inconvenience of non-structurally damaging flood inundation, a lower level of protection may be appropriate (such as the 100-year return period).

2.0 ASSESSMENT OF MAIN CATCHMENTS AND PROCESSES CONTRIBUTING TO DAMAGE

2.1 Geology

The geology and topography of the area around Matata are shown in Figures 2.1.1 and 2.1.2.

2.1.1 Mantling deposits around Matata

The upper-most units mantling the landscape around Matata are young airfall tephras derived from past rhyolitic eruptions from the Okataina Volcanic Centre[8], a explosively active volcano with an eruption record extending back more than 280,000 years. Between them are ancient soils (paleosols) and reworked tephra. Together, the beds of airfall tephras and reworked materials usually amount to a few metres or less in thickness. The airfall layers contain fresh lumps of pumice and the deposits are usually barely-consolidated to soft. The oldest of these relatively fresh tephras is part of the Rotoiti formation erupted from the Okataina centre about 62,000 years ago (C.J.N. Wilson, pers comm., 2005). Ignimbrite is present within the Rotoiti formation along the coastline west of Matata. In the hills around Matata, Rotoiti ignimbrite deposits may be present in isolated pockets. Rotoiti ignimbrite generally contains abundant fresh mineral grains and pumice lapilli, and is loosely consolidated to firm.

Multiple rhyolitic airfall tephra layers, buried soils and other sediments are variably present below the Rotoiti formation across the Bay of Plenty Coast[9]. These range in consolidation from soft to hard and are derived from various Taupo Volcanic Zone (TVZ) eruptions between the 62,000-year-old Rotoiti eruption and the 280,000-year old Matahina eruption[10].

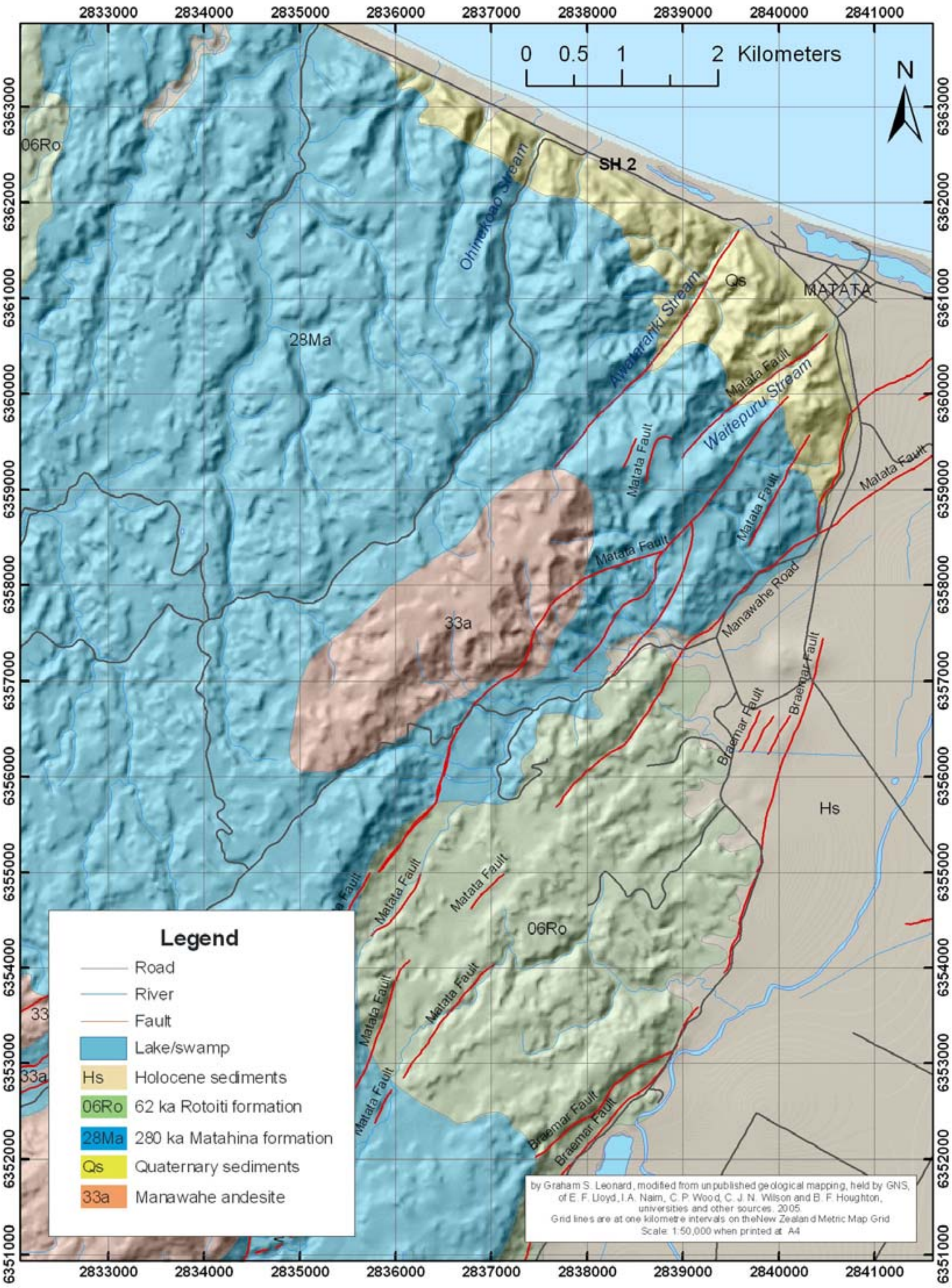

Figure 2.1.1 Geological map of the Matata area showing the distribution of the geological formations discussed in the text, and the major faults recognised in the area. Data from GNS files.

Figure 2.1.2 Topographical map of the Matata area. Section of Topographic map 260-V15 Edgecumbe (2004). Grid spacing is 1 km.

2.1.2 Matahina formation

The Matahina formation was also likely erupted from the Okataina volcanic centre[11]. It is dominated by firm to very hard (welded) ignimbrite, in thicknesses of tens to hundreds of metres, in the areas where it is exposed near Matata. It does not appear in the cliffs behind Matata, and the northern-most extent of Matahina formation appears to be a few kilometres back from the coastal cliffs there. The lumps of pumice within the Matahina ignimbrite are much less crystal rich than those in the Rotoiti formation, and contain a much smaller proportion of dark (iron- and magnesium-rich) minerals. A very-hard, welded horizon within the Matahina ignimbrite, tens of metres thick, forms jointed bluffs in the upper catchments of the Ohinekoao, Awatarariki and Waitepuru Streams. Within the welded ignimbrite pumice clasts have often collapsed to flat, parallel glassy lenses (called fiamme). Many of the harder boulders in the bed of these streams come from this unit.

2.1.3 Sandstone and siltstone

These soft, weak, sedimentary rocks are described by Rae[12] and were laid down 300,000 to 700,000 years ago (in a time interval referred to by geologists as Castlecliffian), before the Matahina ignimbrite was erupted. Sandstone and siltstone constitute the entirety of the vertical thickness of rock exposed in the coastal cliffs at Matata. Matahina formation overlies these rocks a few kilometres back into the catchments[13]. The shallow marine and estuarine sands and silts contain interbedded rhyolitic airfall layers derived from TVZ eruptions prior to the Matahina eruption. These sediments in turn overlie beds of brown, weathered greywacke pebbles deposited some 700,000 to 2 million years ago. These in turn appear to overlie a massive siltstone.

2.1.4 Basement rock

Poorly-exposed Manawahe Andesite (erupted 620,000 years ago)[14] pokes through the Matahina ignimbrite 5-10 kilometres south of Matata, but pieces of andesite have not been noted in any of the stream deposits around Matata. The regional basement is greywacke, which is not exposed near Matata, or in the nearby catchments, but outcrops 10 to 15 km to the west. Several large boulders of what appears to be very hard, fresh greywacke sandstone are present in the bed of Ohinekoao Stream beside SH2, indicating a source of greywacke somewhere in its headwaters.

2.1.5 Source of the boulders

The Matahina formation appears to supply the hard to very hard (welded) ignimbrite boulders that dominate the deposits in Ohinekoao, Awatarariki and Waitepuru Streams. A lesser proportion of boulders are firm to hard siltstone and silty sandstone, inferred to have come from one or more siltstone horizons within the pre-Matahina sediments. Abundant reworked greywacke gravels also are present. In the smaller catchments, between Awatarariki and

Waitepuru streams, no boulders of ignimbrite are apparent, and deposits are composed only of greywacke gravels, and pebbles, cobbles and boulders derived from the siltstones and sandstones.

2.1.6 Offsetting of units by faulting

In a traverse up many of the stream channels south of Matata, an observer will pass up and down through parts of the above sequence of sedimentary units because the larger streams cross back and forth across faults that offset the units.

2.1.7 Faulting and earthquakes

The area of land that forms the broad valley between Matata and Whakatane is part of the geological structure called the Whakatane graben (a *graben* is a technical term, from German, for an area of land and rock that has dropped down between two systems of earthquake faults). A part of the Whakatane graben dropped in the 1987 Edgecumbe earthquake. The area is going down because the eastern and western sides are slowly moving away from one another. In addition, the western side is gradually moving north relative to the eastern side. Matata lies on the western edge of this very active geological structure, in the midst of a zone of faults collectively known as the Matata fault. The valleys of Ohinekoao, Awatarariki and Waitepuru Streams all appear to follow faults that are part of this fault system[15], and there are certain to be other faults, that are not yet mapped or recognised.

The current Matata earthquake swarm appears to be caused by minor, subsurface movement on some of these unmapped faults. They are contributing in a minor way to the overall deformation of the land mass, but the elevation of the land is their only contribution to the debris flows at Matata on 18 May, and to the future risk of debris flows at Matata. These earthquakes appear to be concentrated at shallow depth (about 5 kilometres) in an area northwest of Awatarariki Stream (Figure 2.1.7.1). The area of earthquake epicentres is partly onshore, but extends a few kilometres offshore. The swarm is located shoreward of the epicentre of a moderate earthquake that shook Matata in 1977[16], and the trend of the current swarm is more-or-less on line with the trend of aftershocks that followed the 1977 earthquake. There is nothing particularly unusual about the current swarm of earthquakes[17]. Similar swarms of various durations have happened elsewhere in the Taupo fault belt in the past. Some have been quite brief, and some have lasted for many months. Most have not led any significant damage, but one notable exception was the swarm that preceded the 1987 Edgecumbe earthquake.

While we understand why the earthquake swarm is occurring, we do not know what controls the timing of the earthquakes. The expectation of seismologists is that the current earthquake swarm is more likely to continue in the immediate future than it is to stop. At present, there is no way of telling how big the next earthquake in the swarm will be, nor indeed whether there will be another earthquake in the swarm.

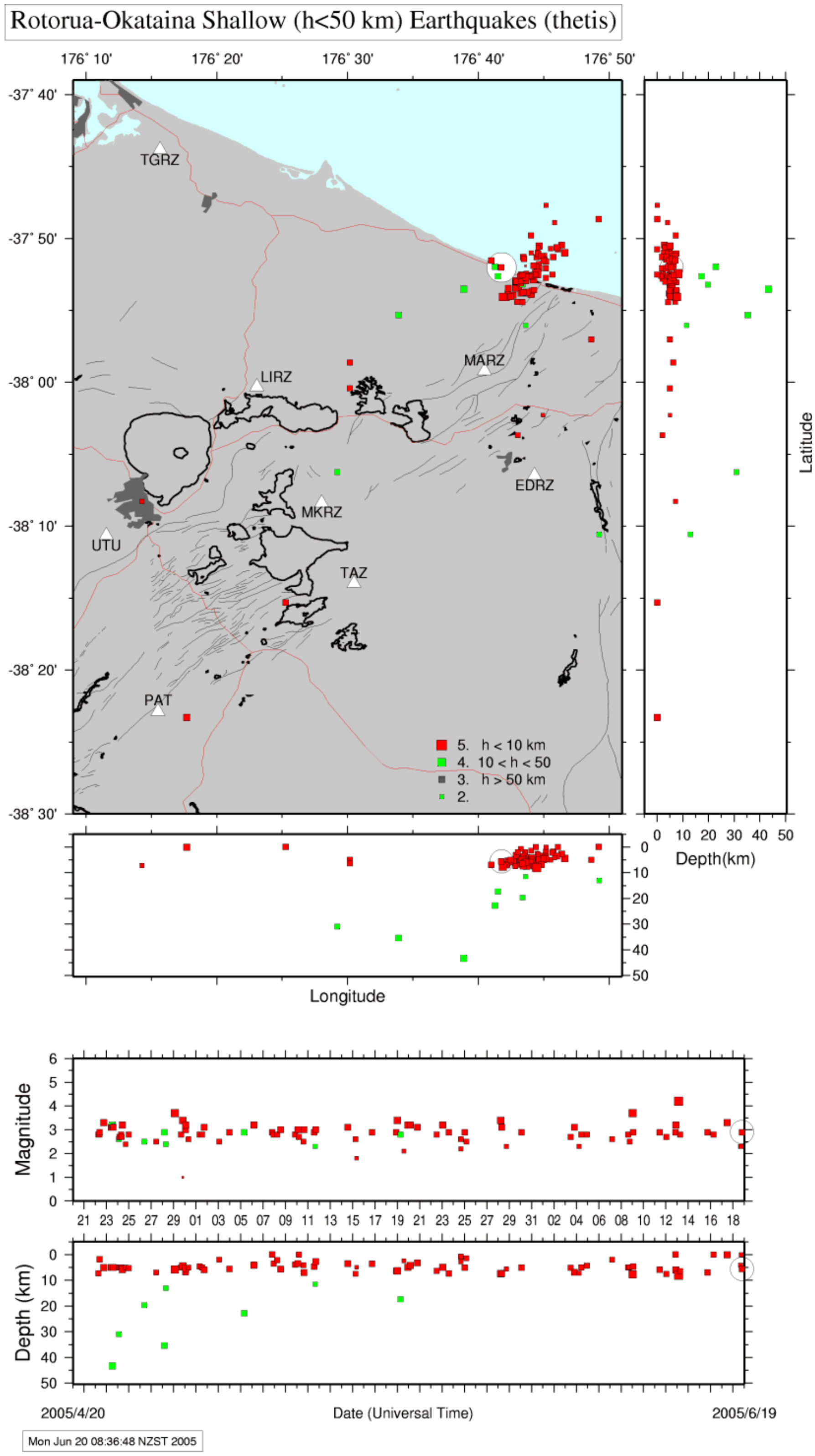

Figure 2.1.7.1 Distribution of shallow earthquakes relating to the ongoing swarm of minor earthquakes near Matata. See http://data.geonet.org.nz/geonews for updated information. Data from GeoNet.

2.2 Geomorphology

The steepland catchments of Ohinekoao, Awatarariki, and Waitepuru Streams to the south of Matata are deeply incised box canyons. They are cut into the mantling deposits and Matahina formation, down to and into the soft, weakly cemented sandstone and siltstone. The soft siltstone appears to be somewhat resistant to erosion and forms the bed and banks of the stream channel from where loose sediment has been scoured by the debris flow. This probably is because the siltstone is more cohesive than many of the other units, and its softness allows it to absorb impacts without fracturing. Boulders of siltstone were carried long distances in the debris flows, even though they fall apart on drying.

Between Awatarariki and Waitepuru Streams, there are smaller, less incised catchments, the largest of which is Waimea Stream. To the south of Waitepuru Stream are tributaries of Awakaponga Stream, which are deeply incised in steep-sided valleys rather than box canyons.

The coastal face of the upland area was trimmed by the sea until about 7000 years ago, forming a coastal cliff. This now is the steep hillslope immediately south and to the northwest of Matata. Since 7000 years ago, sand from Tarawera and Rangitaiki Rivers has been carried northwestward along the coast by waves to form a narrow coastal plain in front of the cliffs. Until engineering work established new mouths for Tarawera and Rangitaiki Rivers, their combined flow reached the sea in the vicinity of Matata, and this is the origin of Matata Lagoon. A large part of the coastal lowland at Matata is formed from sediments eroded from the catchments of Waitepuru, Awatarariki, and the smaller streams in between, and deposited as gently sloping fans in front of the ancient coastal cliff. While a river mouth was in the vicinity of Matata, the fans were trimmed by river erosion to form a minor cliff behind Arawa Street. Trimming caused Waitepuru Stream to cut deeply into the toe of its fan, and it since has deposited a smaller fan, at the foot of the trimmed slope, so that there is now a stepped landscape. This gave substantial protection to historic Matata, and probably is why the site originally was adopted for settlement. As well as being by a bountiful food supply, and canoe access to the hinterland, the elevated fan toe would have been well drained, and the superior forest trees growing there would have indicated a stable site, predisposing it to selection when people first settled the area. Growth of the settlement has caused urban development to spread on to less safe fan areas.

There are four stream fans of main concern to Matata, the fans of Waitepuru, Waimea and Awatarariki Streams, and a smaller stream from the hills between Clarke and Simpson Streets (Figures 2.2.1 and 5.0.1). They are of concern because they primarily are debris-flow fans which have been formed by debris-flow events of the type experienced at Waitepuru, and Awataraiki Streams on 18 May. Such events do not happen often, but they occur frequently enough to have built the existing fans in the last 7000 years, even with a large river episodically trimming them and carrying sediment away to the sea. Debris flows were not active on the two fans between Waitepuru and Awataraiki Streams on 18 May, but this may be an accident of the distribution of the intense rain that triggered the debris flows. The heaviest rain seems to have missed these catchments by less than 500 metres. The steep fans from these catchments provide clear geomorphic evidence that such storms do not always miss them. The deposits of past debris flows can be viewed in cut batters along Pakeha Road below the rail embankment (Figure 2.2.1).

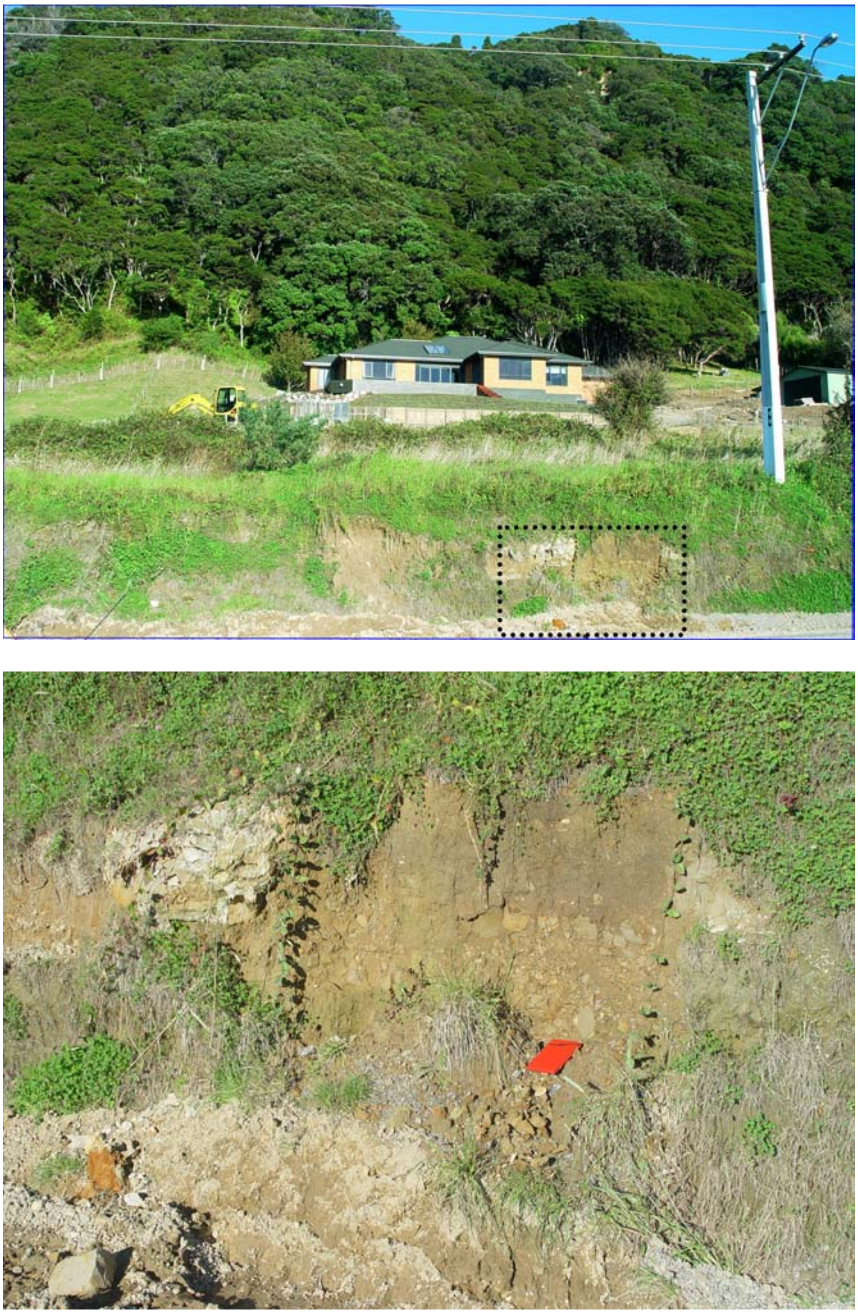

Figure 2.2.1 The deposits of past debris flows can be viewed in batter slopes beside Pakeha Road between Clarke and Simpson Streets. They indicate that the steep fans at the foot of the hillside are the deposits of past debris flows and debris avalanches. Boxed portion of upper photo shown in detail below. Largest boulder in detail is about 500 mm across.

It is probable that large boulders reported to be on the sea floor near Matata[18] are remnants of past debris-flow fans deposited in yet more ancient times when sea level was lower than it is today and debris flows could deposit their loads on the land now seaward of the present-day coastline.

2.3 Effects of geology on headwater slope stability

The weakly to moderately welded ignimbrites and their associated interbeds range widely in erodibility. They stand in high, steep, to very steep slopes above the deep narrow stream channels which are floored mostly on soft siltstone. The more strongly welded components of the ignimbrites are columnar jointed (with regularly spaced cracks) from contraction during cooling from high temperature. These vertical cracks promote ready failure of the strongest rock in the catchment, and the formation of many large to very large boulders in the stream bed. Most of these boulders are too large to move in normal stream flood flows and are moved only by debris flows.

It is the steep slope angles more than the character of the rocks that make the catchments so prone to debris flows. The steep slope angles arise because the catchments are small, but large enough that their streams have cut to the foot of the ancient sea cliffs. The larger coastal catchments further to the west of Matata are too large for debris flows in them to propagate to the coastal plain.

2.4 The storm rainfall

The closest automatic raingauge is near Awakaponga at Grid Reference V15: 412553, about 5km to the SSE of Matata. The 15-minute rainfall record from this gauge (Figure 2.4.1) shows exceptionally high intensity rain between 16:00 and 17:30 hours on the 18th of May, which peaked at about 30.5 mm in 15 minutes (more than 2 mm per minute). Such intense rainfall indicates a very active convective storm cell, typically associated with lightening and thunder.

In his work in the western Southern Alps of South Island, Dr McSaveney found that few landslips occur on slopes when intensities are about 1 mm per minute, more and bigger landslips occur at 1.5 mm per minute, but landslips and debris avalanches occurred widely as intensities approach 2 mm per minute. Critical thresholds for landslips vary in other rock types, depending on how frequently such intensities occur. Rain of the intensity measured at Awakaponga was capable of triggering numerous debris avalanches when it fell on steep slopes in the catchments of the main streams at Matata, and it will do so each time it occurs.

In the intense burst of rain between 16:00 and 17:30 hr, we consider the Awakaponga rainfall to be representative of rainfall that occurred in the hills behind Matata. This is because the event appears to have been a strongly convecting storm cell with a rapidly ascending cumulo-nimbus cloud and much lightning. There is little variation in rainfall with ground altitude with such storms. When such intense storms drift across hill and mountain slopes they leave in their wake a swath of landslips and debris avalanches marking their path.[19]

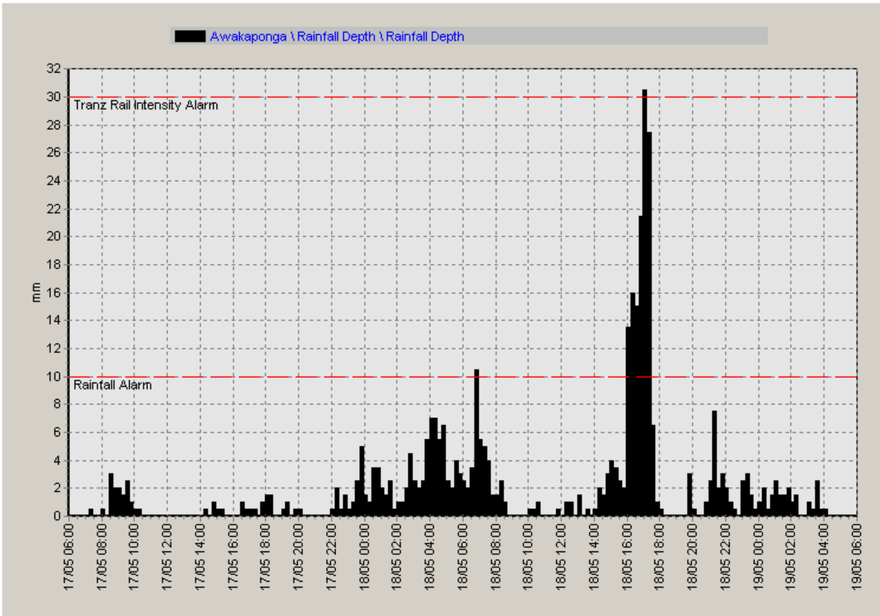

Figure 2.4.1 Histogram of 15-minute rainfall totals at Awakaponga (from Environment-Bay-of-Plenty records).

Earlier rainfall during the day had already saturated the ground in all catchments, but otherwise contributed little to the disaster at Matata. A summary of rainfall recorded by all the Environment Bay of Plenty automatic rain gauges is shown in Appendix 1.

Mr Peter Blackwood of Environment Bay of Plenty[20] reports that the Awakaponga 1-hour rainfall of 94.5 mm is 30% greater than the 1%-annual-excedence-probability (AEP) (sometimes known as the 100-year return period), and is close to the New Zealand record rainfall line (from *NZ Met Service Provisional List - Oct '72*), although this is superseded by later events, notably the 107 mm in 1 hour recorded at Leigh on 30.5.2001. A value 30 percent greater equates to approximately a 500-year return period on the dimensionless Bay-of-Plenty curve. However, as there are little data on such extreme events, the actual recurrence interval for this intensity of rainfall could be less than 500 years.

The 24-hour rainfall of 302 mm at Awakaponga is also 30-percent greater than the 1% AEP value for that site, but it is the rainfall during the brief high-intensity storm that is most important in estimating a likely return period for the debris flow events.

2.5 Land cover and effect of vegetation on stability and erosion potential

Prior to the 18 May 2005 event, the valleys were well vegetated in secondary, largely native forest consequent on logging about 100 years ago[21]. The gentle crests of slopes are in pasture. Wild animals have been moderately well controlled in the area for some time, and the pasture and forest cover were in excellent condition prior to the event[22], and are not substantially depleted now (Figure 2.5.1). We estimate that only a small proportion (a few percent) of the catchment areas was affected by landslides, debris avalanches and debris flows during the storm, although in most of these affected areas, vegetation removal has been total.

Figure 2.5.1 Aerial view of Awatarariki Stream showing the excellent condition of the forest cover save for the scars of recent debris avalanches caused by high-intensity rain.

Immature (sub-mature) forest trees falling from the slopes and eroded from the channel banks contributed to the large volume of woody debris now on the fans (Figure 1.3.4). The forest cover has neither inhibited, not contributed to initiating the debris flows. The trigger was the very high-intensity rain. Had the forest cover been more mature (larger trees), it is possible that debris flows could have formed at a lower threshold of rainfall intensity because the weight of the trees is one of the factors that contributes to the instability of the slope. In addition, larger trees would have been more of an impediment to flow, and so larger, deeper, and more destructive debris flows might have been the outcome.

Root strength is a factor contributing to the strength of the soils on the slopes, but the root strength of the existing forest is little different from that to be expected if the forest cover were fully mature. Also, under the extreme rainfall conditions, many of the landslips were from failure of the bedrock beneath the root mass, and so root strength contributed mostly to the size of the falling masses and little to whether or not they fell.

Rainfall interception was not a useful mitigating factor in the storm because the forest and soils already were wet from earlier rain, in the hours before the deluge (Figure 2.4.1).

Maintaining a healthy forest cover has many beneficial effects, however, the storm of 18 May was too extreme, and way beyond the capacity of any forest cover to protect Matata from major debris flows and flooding. The risk of future debris flows caused by such extreme rainfall will not be materially changed by enhancing the present vegetation cover.

2.6 Recent seismic activity and its effect on stability and erosion potential

The ongoing swarm of small earthquakes is at shallow (~5 km) depth within 5 km of Matata, mostly to the west and northwest (Figure 2.1.7.1). They are contributing in a very minor way to the overall deformation of the land mass, but they did not contribute to the severity of the debris flows at Matata on 18 May, and they are not contributing to the future severity or risk of debris flows at Matata.

The earthquakes obviously are shaking the land as well as the people, and it is likely that they are loosening material on the steep slopes. It is possible that some of the larger of the small earthquakes have caused small landslips, especially those that have occurred while the catchment has been very wet from rain. But the present earthquake swarm was not a factor in influencing the course of the May 18 debris-flow events (the very heavy rain was quite sufficient on its own). There have been similar earthquake swarms in the area in the past as well. The landslips that fell in the catchments behind Matata during the strong shaking of the 1987 Edgecumbe earthquake would have been a greater influence on 18 May 2005 because they delivered to the valley bottoms part of the sediment that was eroded by the debris flows on 18 May.

Landslides from future strong earthquakes, in the current swarm or later, will contribute to renewing the in-channel sediment storage that was depleted on 18 May, but there also will be other contributing events such as landslides triggered by rain.

2.7 Sediment transport processes active during the storm event

The primary causative events that inevitably led to the debris-flow damage at Matata were landslips of the type termed *debris avalanches* — these are relatively thin slabs of rock that detach along cracks in the rock parallel to the rock slope, together with all of the vegetation and soil mass attached to the slab, and all, or most of the vegetation and soil mass on the slope below – all the way downslope to the stream channel (Figure 1.3.3). As they drop, they appear to liquefy, so that the mass slides and flows to reach the valley bottom as a dense fluid. These debris avalanches were triggered by the catchments' response to the very high intensity rain. As discussed earlier, it is normal for rainfall intensities of about 1 mm/minute to cause some shallow landslips on steep slopes, but as rainfall intensities approach 2 mm/minute, many more shallow landslips occur widely, as the capacity of the rock and soil to carry away the infiltrating rainfall is overwhelmed. The most susceptible slopes are where either or both of surface and subsurface flows converge — the hollows in the present landscape, or in the ancient landscapes buried by the various tephras. Most of the shallow landslips in the catchments of Waitepuru and Awataraiki Streams were debris avalanches, and most of them reached to stream channels in the valley bottoms.

Figure 2.7.1. Grooves gouged into the soft siltstone by passing boulders in the debris flows. The parallel grooves indicate that the mass of the debris flow slid past the cliff, much like a glacier (but of course far faster).

As the debris avalanches reached stream channels, they transformed into debris flows as a matter of definition and not of process (debris flows are essentially debris avalanches, but confined to a channel). As noted in Section 1.3, debris flows are highly erosive, saturated masses of rock rubble, soil and vegetation. They travel faster than the normal flooded stream flow, and so they pick up the contents of the stream, and most of the more easily eroded stream bed, down to the local bedrock, and thereby bulk up in volume as they proceed down the channel. The front of a debris flow can have the consistency of wet concrete, but only where it has opportunity to thoroughly mix with the entrained floodwater. Until it gets mixed in, some of the floodwater can be pushed in front of the debris flow. Behind the debris-flow front, the debris flow can be very water like. A key characteristic of debris flows is that the water, fine sediment and boulders all behave as a unit and move together at the same speed; in effect the water is forced to move at the fast speed of the sediment.

The thicker parts of a debris flow move somewhat like a deforming plug, and the boulders and logs in it can scrape the channel floor and sides leaving in their wakes many sets of parallel grooves, especially in the soft cohesive siltstone. Such grooves can be seen in the valleys of Waitepuru and Awatarariki Streams (Figure 2.7.1).

When debris flows encounter wider channels, they tend to deposit sediment rather than erode more sediment. Deposition occurs particularly up-stream of channel constrictions, and on channel gradients of less than about 6°. Debris flows are only able to flow for relatively short distances where they are unconfined and on gentle slopes – such as on the fan slopes through Matata. On such slopes they slow, then stop. The water draining from them results in a *debris flood*. The water flow is generally a hyperconcentrated flow, which is thicker than a normal sediment-laden flood of water and able to move much more bed-material load than a simple flood because of its greater density. At Matata, the debris floods were the inevitable and direct consequences of the debris flows. Although it was possible to have a debris flood without a debris flow from the storm that hit south of Matata, it was not possible to have a debris flow without a debris flood beyond it; there was just so much water and fine sediment to drain away.

Because the floods that extended beyond the debris flows at Matata were from the water that had been picked up by the debris flows and transported more rapidly to the fans, the floods were larger and much more extensive that could have occurred had there been flooding alone, without the debris-flow phases. In effect, the fast debris-flow process sped up the times of concentration of the flood peaks, resulting in higher peak flood discharges.

During the events of 18 May, two of the smaller streams do not appear to have been affected by debris flows. This appears to have been because they were not exposed to the highest intensities of rainfall at which many shallow landslips occur. In our short walk up the channel of Waimea Stream from the railway, we saw much evidence for hyperconcentrated flow and debris flood (poorly sorted, but laminated deposits, with very little strength), but no evidence of a debris flow. West of Waimea Stream by some 500 m, a newly built home at the apex of a debris-flow fan was slightly affected by sediment mobilised in the bed of the small flooded creek, but the minimal damage around the house indicates that no debris flow occurred there.

2.8 Possible damming of streams

In the channels of Awatarariki Stream and especially Waitepuru Stream, there is clear evidence of channel damming by landslides, but all of the evidence that we saw was for landslides and dams that were consequent on the severe erosion of the channel banks by the passage of large debris flows. That is, they occurred during and after the debris flow; some, so much later, that the dam material has yet to be overtopped by floodwater (Figure 2.8.1).

Figure 2.8.1 A recent small stream-channel landslide. It fell after the debris flow of 18 May, and had yet to be overtopped by water flow.

Evidence suggests that during the high-intensity rain storm there was too much water in the streams and the debris avalanches were too fluid for damming to have been the initiating trigger for the debris flows. There were possibly hundreds of debris avalanches of many sizes, leading to many debris flows when they reached channels. Almost all of the minor channels feeding into tributaries to the main channel carried debris flows. They coalesced as tributaries joined, eventually linking into one, or a few large surging flows in each catchment. Debris flows in steep channels typically travel at higher velocities than floodwater in the same channel, and the Awatarariki and Waitepuru debris flows would have picked up water from their channels as they raced towards Matata. Most debris flows have large pulses, and constant flow is never seen. Pulsing flow, when seen at Matata, could be interpreted as resulting from intermittent damming, but this is not the cause of the pulses. Once initiated, the debris flows were too powerful for the many trees to have even temporarily blocked flow. Because debris flows are so highly erosive, and scoured much of the channels to bedrock, some of the slopes adjacent to the channels were undercut, and fell into the tails of the debris flows, or after the first debris flows had passed. Some of these secondary landslides were quite large, and could have temporarily constricted the flood flow after the passage of the first debris flow. Some, however, fell long after the flood had passed (days after), and still remain in the channel. They are a part of the slope process that will intermittently replace the channel sediments that were depleted by the erosive debris flows on 18 May.

Small dams probably formed in the catchments from landslides during the 1987 Edgecumbe earthquake but they did not give rise to damaging debris flows. This possibly is because the landslide dams in the steep, narrow channels then were too small to store up sufficient water. A larger landslide in a future earthquake is conceivable, and could result in a significant flood, or even another debris flow when the dam it forms is breached. We saw no evidence to suggest that such landslide dams contributed to the severity of the event on 18 May. In our flight over the area, we saw widespread evidence that the severity of the event was caused by numerous debris avalanches coalescing and contributing to the growth of debris flows in almost every one of the many tributaries of the streams. These in turn coalesced to form the debris flows that struck parts of Matata.

What we know of the rainfall intensities on 18 May, and what we know of the distribution of landslips, debris avalanches and multiple debris flows in the catchments are quite sufficient to explain the severity of the events that occurred at Matata. We saw nothing to support a hypothesis that the events were caused by breakout floods from debris dams.

Figure 2.9.1 Debris flows cut a distinctive U-shaped channel that is highly diagnostic of repeated debris flows over a long time.

2.9 Channel erosion

Debris flows are one of the more powerful agents of erosion. They produce a very distinctive, highly diagnostic, crudely U-shaped channel form – which is widely present in the valleys behind Matata (Figure 2.9.1). The Matata U-shaped channels were not formed on 18 May, the bedrock channels have always had this form, but for most of the length of channel, the shape previously has been disguised by secondary infilling, which now has been largely removed by the debris flows.

Much of the sediment that now is in Matata did not come directly from the initial debris avalanches from the valley sides. It was picked up by the debris flows as they eroded their channels. The role of the debris avalanches was to initiate the debris flows. Once initiated, the debris flows were self-sustaining until they reached the lowland fans at Matata.

2.10 Previous debris flows at Matata

There is irrefutable evidence for previous debris flows at Matata. The evidence shows that large prehistoric debris flows built the land beneath Matata over the last 7000 years. One of the previous debris flows delivered the huge boulders that were used as landscaping features on the fan of Awatarariki Stream before 18 May (Figure 2.10.1).

Figure 2.10.1 Huge boulders from past debris flows are used as landscaping features. They provide clear evidence of past debris flows at Matata.

Dr, The Honorable Ian Shearer lists 28 floods that have occurred in the eastern Bay of Plenty in the last 137 years[23]. Some of these have affected Matata. Several of these can be confirmed as debris flows. One in 1869 destroyed a flour mill on what we presume to be the fan of Awatarariki Stream[24]. The boulders from another in 1950 were illustrated in the *Whakatane Beacon* of 1 June 2005. This is likely to have been from Waitepuru Stream because historical vertical aerial photographs held by GNS bracketing this time show evidence of a debris flow in that stream between 26.9.44 and 18.4.61. Floods in 1906 and 1939 may also have been associated with debris flows[25], although we are unable to see features on 1944 aerial photographs consistent with a large debris flow in 1939.

3.0 QUANTITY OF SOLID MATERIAL AND DEBRIS DELIVERED FROM THE CATCHMENTS ON 18 MAY

We have only been able to make crude estimates of the volumes of solid material deposited at Matata. For Awatarariki Stream, the fan length is about 300 m and width, about 300 m. An average sediment depth of about 2 m leads to a volume estimate of about 100,000 m^3 on the fan. Some 10% of this is "large woody debris" – the larger remnants of the trees (Figure 1.3.4). Perhaps as much again of sediment and woody debris did not stop on the fan and is now in the lagoon and beyond (Figure 3.0.1). In all this adds to a total estimated volume of 200,000 m^3.

Figure 3.0.1 Much of the fine sediment (mostly sand and silt) did not stop on the fan of Awatarariki Stream, but was carried into the Matata Lagoon.

The volume of debris deposits from Waitepuru Stream is less than half the volume from Awatarariki Stream, say 100,000 m^3.

The large boulders are the lesser part of the total volume. Most of the material is sand and silt, and much of this passed into the lagoon where a lot of it remains.

4.0 LIKELY RESPONSE TO FUTURE HYDROLOGICAL EVENTS

4.1 In the immediate term

This is in relation to silt remaining on slopes in the catchments and recently deposited in the channels, and its vulnerability to movement downstream in rainfall and associated runoff events expected at least several times a year.

The 18 May event has destabilised some of the catchment slopes. The effects of this can be seen as the numerous fresh landslides that obviously have fallen since the debris flows and high stream flows of 18 May. The materials now in the channels are generally looser and more erodible than the material there before. The hydrological response patterns of the streams probably are altered, particularly in the larger catchments of Waitepuru and Awataraiki Streams. These catchments now have significantly less opportunity for retention of flow as groundwater in channel alluvium. Stream flows may now be more flashy when it rains. There may be more episodes of hyperconcentrated flows, indeed an unnamed stream near Ohinekoao Stream was flowing in hyperconcentrated flow on 24 May while in normal, non-flood flow (Figure 1.3.5).

Although perhaps 200,000 m^3 of loose sediment went from the Awataraiki catchment on 18 May, much more than that remains on the slopes and in the channel. Not all of this is readily available to be eroded in the next debris flow, and so there is not much likelihood in the immediate future for another debris flow as large as that on 18 May if the same high intensity storm were to recur. The processes of mass movement that redistribute the loose sediment within the catchment are relatively fast, particularly while many of the slopes are disturbed from the last event. They are fast enough that the processes can be seen to have been operating in the weeks since the event, with many minor landslides into the stream channel (Figure 2.8.1).

In the small catchments between Waitepuru and Awatarariki Streams, sediment storage is largely unaltered, and they have the same potential for debris flows and debris floods as they had before 18 May.

4.2 In the short term (up to ten years)

Debris flows are likely to be significantly more frequent within the disturbed catchments for at least several decades as a result of the recent disturbance. They are unlikely to be as large as the recent events, because the sediment stored in the channels has been significantly depleted, and so most debris flows are likely to stop before they reach the fan head, but some may reach onto the fan. Although there is less sediment available now, there still is enough for a major debris flow, should the appropriate meteorological circumstances arise. More extreme rainfall intensities than seen in this event may be required to trigger debris flows as large as on 18 May.

Hyperconcentrated flows during floods and freshes may occur as a matter of course for the next few years if the small stream observed in hyperconcentrated flow at normal flow levels is a guide.

4.3 In the long term (up to 1,000 years)

The presently depleted in-channel sediment stores already are being replaced by landslides into the valley bottoms. Within a hundred years or so, the catchments will look little different from the ways they were before May 2005, and they will be capable of responding in similar ways to a similar storm. The peak rainfall intensities in the storm of 18 May, though high, were not the greatest possible rainfall intensities for the area, and so when the channel storages are sufficiently replenished the catchment will be capable of producing even more severe debris flows than those of 18 May. In particular, the catchment of Waimea Stream did not experience a major debris flow through its lower channel on 18 May, and its sediment supply is not depleted. We saw the deposits of a past debris flow in the banks of the stream, and so we know that it is possible for large debris flows to flow out onto its fan.

5.0 AREAS AT RISK FROM DEBRIS FLOWS AND DEBRIS FLOODS

The precedent of the event of 18 May indicates that all of the fan surface of Awatarariki Stream is at risk from future debris flows and debris floods (Frontispiece top), whereas this is not the case for the fans surfaces of Waimea and Waitepuru Streams. This is because all of the fans east of Awatarariki Stream have been trimmed at their toes by Tarawera River. As a consequence, the eastern streams are incised into their fans at the toe, so reducing the flood and debris-flow hazard on their northern parts (Figure 5.0.1). The events of 18 May, and other historical events demonstrate that since diversion of Tarawera River, the incised channels have been rapidly filling in (Arawa Street is on very young land). The entire fan landscape dates only from the last 7000 years, and has formed mostly in events of similar (and larger) magnitude to that of 18 May, so it is apparent that it would not take many more such events before Waitepuru Stream has reclaimed most of the fan currently unavailable to it because of the channel incision. Hence, we can use the distribution of damage on 18 May to delineate the areas currently at risk on the Waitepuru and Waimea fans, infer that these areas used to be a little smaller, and are growing larger in each succeeding event (Figure 5.0.1), as the incised channels are infilled.

The rates of growth of the areas at risk from flood inundation and debris flows are of course slow relative to the age and rate of growth of Matata, but mitigation strategies that recognise the growth pattern are more likely to be successful in the long term, than those that do not. Recognising the pattern does not necessarily mean accepting it, measures could be adopted that are intended to counter it.

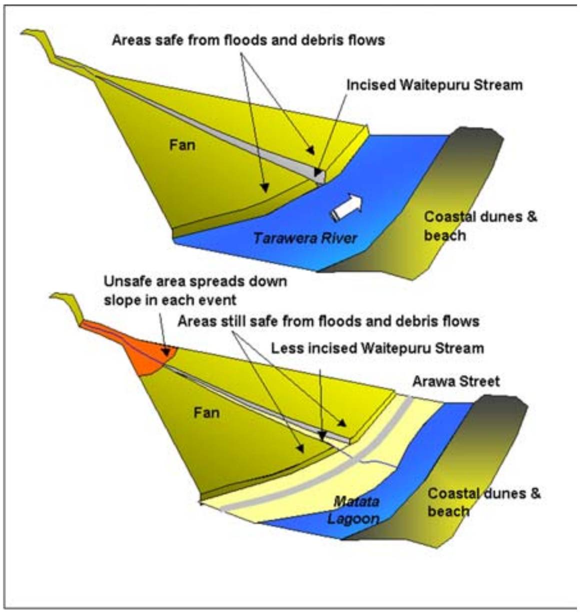

Figure 5.0.1 Cartoon illustrating how trimming of the fan toe at Waitepuru Stream created areas of land safe from flooding and debris flows. Since diversion of Tarawera River, continuing deposition on the fan is causing the safe area to shrink. More and more of Matata will be at risk from flooding and debris flows unless this trend is countered.

The broad areas at risk from future debris flows are relatively easily delineated for much of Matata. The distribution of damage in the 18 May event is a most reliable guide (Frontispiece and Figure 5.0.2), but this distribution was predicated by the particular pattern of intense rainfall over the area. Had the area of intense rain been about 500 metres or so (less than a quarter of its apparent 2 km width) further northeast of its apparent zone of highest impact, it could have had a much more devastating effect on the town. It would likely have triggered large debris flows in all of the small drainage basins between Awatarariki and Waitepuru Streams, as well as debris avalanches off the faces of the coastal hillslopes above Matata. Although the railway offers some protection for some of the homes along Pakeha Road, it offers only partial protection as was demonstrated at Waitepuru and Waimea Streams on 18 May.

Although quite extensive areas of Matata currently are at some level of risk from debris flows and associated debris floods, this is because there are no works in place intended to mitigate the hazard. The areas at risk of damage can be significantly reduced by relatively modest engineering works. They can be reduced even further by less modest works, but they can not be eliminated.

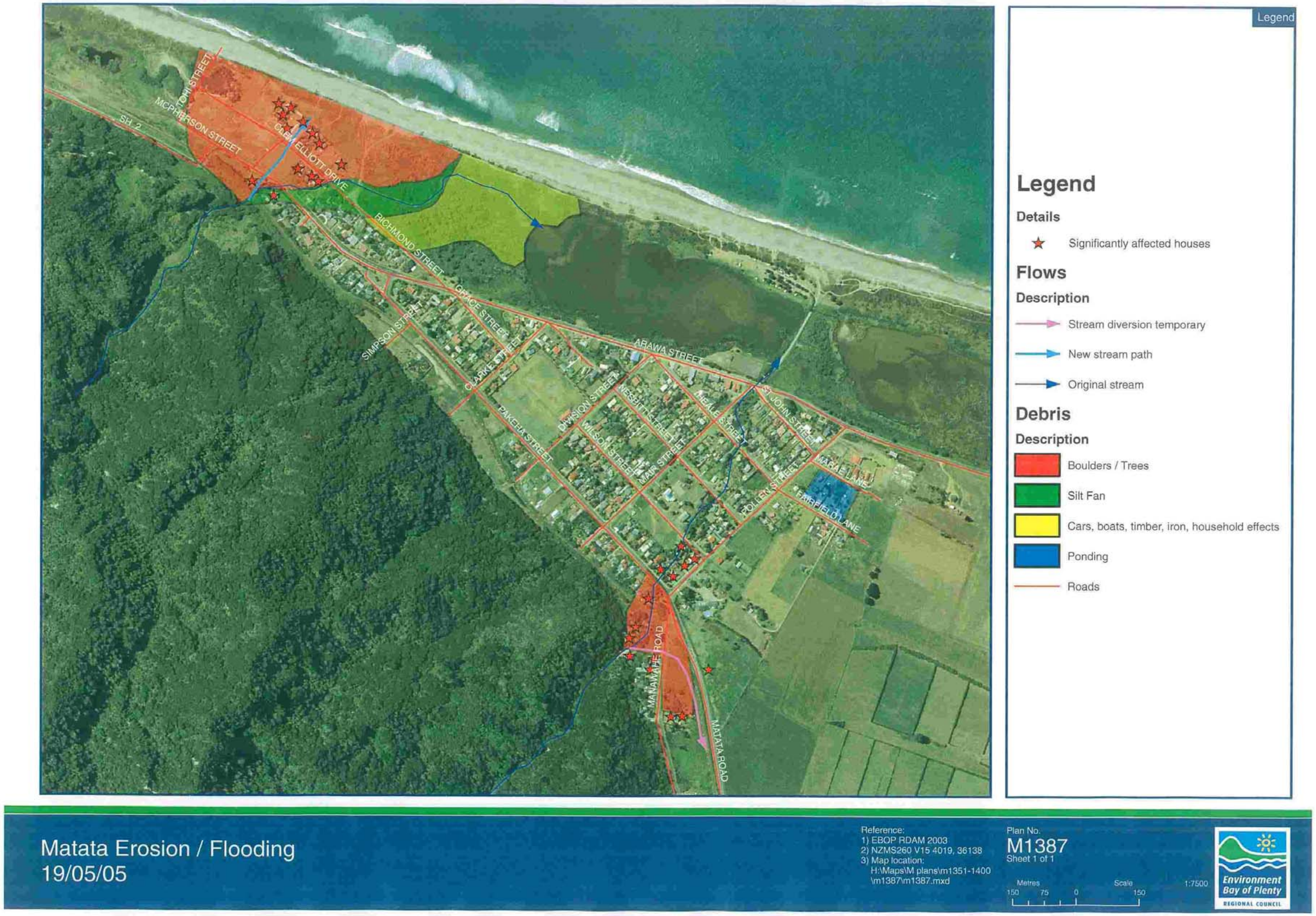

Figure 5.0.2 Distribution of damage at Matata from the 18 May event.

6.0 POSSIBLE WORKS OPTIONS TO MITIGATE RISK AND MINIMISE THE AREA AFFECTED IN FUTURE EVENTS.

All information that we have points to debris flows being relatively rare, but extremely damaging events at Matata. The debris flows of 18 May appear to have been by far the largest of four separate debris-flow events reported to have affected Matata since 1868. That is, the probability of debris flows at Matata is something like once in 35 years or so, but the probability of debris flows as large or larger than those of 18 May may be only once in 500 years or so. Once in 35 years is an unacceptably high probability even for flood inundation, and when the added danger of the debris, with greater damage to property and more danger to life is taken into account, the level of risk is very high, and at a level widely acknowledged to be unacceptable for dwellings.

It is clear that the 18 May debris flows were structurally damaging to all buildings and bridges in their paths. At several locations, the associated debris floods also were structurally damaging. Because of the structural damage, it is appropriate to consider a higher level of protection for debris-flow inundation than would normally be provided for flood inundation. To match other structurally damaging hazards such as earthquakes and strong wind, it is appropriate to choose a high level of protection such that there is a 90% probability of the structure lasting 50 years without being destroyed by a debris flow (an event with 10% probability in 50 years has approximately a 500-year return period). It is fortunate that the 18 May events seem to be of the order of this rare probability (based on the rainfall intensity at Awakaponga), because this provides a sound basis for the design of works to mitigate the debris-flow risk. Whatever measures are taken, they ought to be capable of preventing building damage in events of at least the magnitude experienced on 18 May. In addition, the measures taken should not of themselves make the situation more dangerous in even larger events. That is, we have to acknowledge that it is not possible to provide protection from every conceivable event, and should ensure that the method of protection provided does not cause additional danger when the works are overwhelmed in much larger events. Ideally, the works should still reduce the danger in such overwhelming events.

Four broad options are available to mitigate debris-flow risk. A combination of all four options probably is needed, because the present risk is so high. These options are:

- debris detention (somewhere in the catchments);
- debris deflection (on the fans);
- building regulation (prohibition of building on areas intended to be the paths of future debris flows and debris floods); and
- warning (and evacuation) through early detection of severe storms (regional-scale, high-resolution numerical weather modeling, and regional tracking of storms with weather radar are viable options used elsewhere in New Zealand). This can mitigate the risk to life, but does little to protect property.

On 18 May, the railway created a significant debris-detention basin at Waitepuru Stream. It is thus evident that the design criteria for an effective debris-detention basin are not too onerous. The railway embankment also served to deflect part of the debris flood.

A debris-detention basin (Figure 6.0.1) is not intended to stop all sediment. Its purpose is to stop the boulders and logs, and to permit the finer material and flood water to be more readily controlled (maintained in a designated floodway). As with such devices that stop sediment movement, a debris-detention basin requires regular inspection and maintenance to ensure that it retains enough capacity to contain a future debris flow. This is a more costly commitment than merely maintaining large berms.

Figure 6.0.1 A debris-detention outflow structure from a basin protecting a northern suburb of Vancouver, Canada.

Debris-detention basins are widely used in other countries to mitigate debris-flow damage, but they are recognised to have the potential to make situations more dangerous when they are overwhelmed by events that are larger than those they were designed to cope with. In particular, the illusion of safety from large events may lead to more intensive development of the "protected" area, so that averaged over time, the overall risk of damage is increased rather than decreased. For example, a debris-detention basin might be designed to protect $10 million in assets from debris flows of up to 500-year return period. This might be such a level of protection that over time the community may become oblivious to the hazard and be attracted into the area. By the time an even rarer, and larger debris flow came along, the damage to protected assets might total $100 million, whereas the damage might be $10 million, or less, in the same event if no protection were provided.

6.1 Regional or local warning systems

We note that Environment Bay of Plenty currently uses telemetered rainfall and river-stage information as the basis for a warning system for flooding. Neither point rainfall measurements nor stream flows provide adequate bases for warning of an impending debris flow at Matata. Most storms with a potential to trigger debris flows are localised convective cells, moving in some broader weather system. Many will approach Matata from the sea, but as demonstrated at Matata on 18 May, they need not pass directly over Matata, or any other particular point where a rain gauge might be sited. It is not feasible to space telemetering rain gauges close enough to guarantee that one or more will record the peak rainfall before it does its damage. Also, debris flows move faster than stream flows through the same channel and so no adequate warning can be obtained from stream flow. Trip wires and other devices have been used elsewhere to warn when debris flows are traversing a channel. They are useful for closing transport corridors, but are not widely advocated for warning for evacuation of residential areas.

Weather radar is widely used internationally to warn of the proximity of severe weather. Significant areas of New Zealand are within the range of currently operating weather radar systems centred on Auckland, Wellington and Christchurch. These are financed principally by providing warning to aviation of severe weather, and have not been used to warn the public in New Zealand, although they could be. The Bay of Plenty area is not usefully served by the Auckland, or any other weather radar. A weather radar centrally located in the Bay of Plenty region could provide adequate warning of severe weather for many purposes in the region. It may not need to meet the same specifications as the radars at the three centres above, but it does require dedicated staff, and to operate with 24-hour, 7-days-per-week capability, so the equipment is a small part of the total cost. A radar-based warning system can be regional in extent, but it requires an effective means of promulgating any warning to specific residences likely to be affected along a projected storm path.

6.2 Mitigation options at Awatarariki Stream

Awatarariki Stream has an area some 400m long and 40m wide near the former quarry which appears to be suitable for retention of boulders and logs. A structure, such as is illustrated in Figure 6.0.1, placed at the lower end of the area of the former quarry would be suitable, although it is a little higher that required for Awatarariki Stream, because the gradient of the channel there is less steep than in this example.

If a deliberate debris-retention structure is not used at Awatarariki Stream, then the railway culvert (or future bridge) becomes a default retention structure, but as was demonstrated on 18 May, the storage area behind it is insufficient to contain all of the debris. Were a future debris flow to spill from this unintentional detention basin, its path currently would be unconstrained, and there is little scope to constrain it, because of the need for trains to pass by. To overcome this problem, it is necessary that the railway bridge be constructed to pass whatever issues from the mouth of the gorge, whether this be a debris flow with boulders, such as came on 18 May, or a hyperconcentrated flow with the boulders strained out by some upstream structure. The design of a channel capable of safely passing a debris flow as large as occurred on 18 May is not a difficult task; such a channel would look very similar to the gorge immediately upstream. If the channel under the railway is not designed to pass future debris flows, then the railway becomes a significant contributor to the future inundation hazard on land below it, because it prevents any possibility of control of flow in future events.

The SH2 underpass (either in its form on 18 May or in an extended form) is not a viable alterative debris-flow route, because debris flows tend not to make sharp bends without piling up, and taking more direct routes if they are available. A designed debris-flow channel should be as straight as possible for the local situation and sharp bends must be avoided.

Although it technically is feasible to get future debris flows to pass under the railway, it is not technically feasible to cause them to continue all the way down the fan. The fan gradients are too low, and any debris flow will slow, and stop somewhere on the fan. Hence, any mitigation on the fan must safely cope with whatever volume of sediment might be deposited there, whether or not some sediment may have been detained in the quarry area. A strong, erosion-resisting bund several metres high, and passing between the rail bridge and the foot of the fan could be constructed to keep a hyperconcentrated flow from spilling into existing (surviving) areas of Matata that are on the Awatarariki Stream fan. These include **all** of the inhabited area that was affected by the sand-and-silt-laden flood inundation from Awatarariki Stream in the western sector of Matata on 18 May. Obviously, if the option of a debris-detention basin is not taken up, the bund on the fan would have to be much more substantial and robust in order to withstand the debris flow, and maintain capacity against overtopping during debris-flow deposition.

To be effective, a bund would have to be constructed on the Matata-side of the stream, and the portion of the fan to the west of Matata would remain at risk of future debris-flow, and flood inundation. More land could be retained in urban use if the stream were shifted to a more northerly course on the fan – essentially to the course it adopted immediately after the 18 May debris flow. About half of the total Awatarariki Stream fan area should be left for the stream to allow for deposition in debris floods, and to avoid creating increased danger in large debris flows that exceed the capacity of any sediment storage upstream.

In an integrated debris-flow mitigation for the railway, SH2 and the western edge of Matata, a combination of debris-flow retention structure in the quarry area, and a bund from the rail bridge to the toe of the fan to deflect future floods and hyperconcentrated flows is likely to be feasible and economic. Maintenance of any debris-detention structure may be a significant ongoing cost. This structure also will accumulate sediment during floods without debris flows, even though it is intended to let finer sediment pass through. The accumulated sediment must be removed to maintain the storage capacity with accepted safe limits.

6.3 Mitigation options at Waitepuru Stream

Waitepuru Stream lacks a conveniently wide channel section above its fan head, and if the channel there were to be used to store debris-flow boulders, the debris-detention structure would need to be higher than that illustrated. A higher structure potentially leads to greater danger immediately downstream when the structure inevitably is overtopped. A lower structure is possible if it is built on the fan head, where there were homes before 18 May 2005. The further out on the fan it is, the lower it needs be to achieve the same potential storage. The choice of location is one of economics, balancing property values against cost of the works, and not one of debris-flow dynamics. Note that because of its distance from the fan head, the low embankment of the railway was sufficiently high to stop most boulders on 18 May.

Here, as at Awatararariki Stream, the intention of a debris-detention structure is to take out the boulders and the logs. It will not take out all of the finer sediment, or reduce the flood flow, and so other measures are needed to safely route the floodwater through Matata to the lagoon. Where Waitepuru Stream is deeply incised into the toe of the fan, safely routing the floodwater is not an issue. As it is not deeply incised at the fan head, strong bunds are needed to guide future hyperconcentrated flows. These can be guided to the existing incised channel, in which case, they would pass through areas of existing homes, or they can be guided to the east of Matata where the upper fan area currently is non-residential farmland. Either is technically feasible, but both have social and economic implications that need to be considered.

6.4 Mitigation options at Waimea Stream

Just to the southwest of the railway, Waimea Stream divides into two tributaries. We saw no evidence of an 18 May debris flow in the lower portions of either tributary, but both carried hyperconcentrated flows resulting in debris floods. There may have been small debris flows higher in their headwaters. Evidence seen in old sediments exposed in the banks of the stream indicated that debris flows have reached the fan head in the distant past. We saw nothing to indicate to us how often such debris flows reach the fan head, and so could not readily determine if the debris-flow danger is so high that it should be mitigated. People in the houses in the immediate vicinity (northwest of the top end of Mair Street) certainly should be informed of the hazard.

Apart from the unquantified debris-flow danger, there is a danger from hyperconcentrated flood flow in less extreme events. Mitigation of the flood hazard currently is hampered by the inadequate capacity of the culvert under the railway to safely carry flood flows of Waimea Stream, even if it were to be more adequately maintained than it appears to have been before 18 May. The present culvert may be adequate to meet the needs of the railway, but its presence endangers properties down slope. Without an adequate culvert, there is no means of controlling where future floodwater will go.

If future hyperconcentrated flows safely pass the railway, there is need to route them to the lagoon by the shortest and steepest path, constrained in an adequately deep channel where there is no existing incised channel. The choice between a lined channel or otherwise erosion-resistant berms are options to be considered based on feasibility, economics and aesthetics.

6.5 Mitigation options at Ohinekoao Stream and others in the vicinity

When the road that now is SH2 was constructed along the coast west of Matata, Ohinekoao Stream made a right-angle bend as it exited from its gorge and flowed down the extreme left-hand side of its fan. As a consequence, the Ohinekoao Stream bridges of both SH2 and the railway are offset from the natural direct path of debris flows issuing from the gorge. In this geometry there are no economically feasible mitigation works options available to avoid debris-flow damage from Ohinekoao Stream, because the future path of debris flows cannot be controlled. The road and rail may be repeatedly damaged by floods and debris flows, and damage to the camp ground can only be mitigated by avoiding this area (i.e. by building regulation). Realignment of the bridges with the gorge outlet would increase the mitigation options by allowing the option to route future floods and debris flows under the road and rail through a lined channel, and thereby control where they would encroach on the camp ground. The capacity of the bridges would have to be sufficient to enable them to pass debris flows.

6.6 Mitigation options at Awakaponga Stream

Although there were debris flows in the headwaters of some northern tributaries of Awakaponga Stream, the damage done was not directly from debris flows, but from a hyperconcentrated debris flood which drained from the front of a debris flow and spread widely on the lowland fan of Awakaponga Stream. The most damaging flood flow was from a single tributary, where a debris flow stopped some several hundred metres upstream from any dwelling and the lowland fanhead of the main stream. Subsequent to the event, large boulders from the flood have been piled at the mouth of this tributary to create a large, erosion-resistant bund which is capable of deflecting hyperconcentrated flows from the immediate area of the nearest dwellings and other buildings. This bund is well placed, but it needs to be extended a little further downstream at a lower height to be fully effective against rare, structurally damaging flood flows. Also, its construction is permeable, but it could be made less permeable by covering it with finer sediment and soil.

The bund described above also provides partial protection from inundation for some properties further east on Manawahe Road, but other works are needed elsewhere if these properties are to be adequately protected from inundation by Awakaponga Stream. The small community around the intersection of Manawahe and Caverhill Road perhaps is aware of their inundation hazard from past events. They do not face necessarily structurally damaging flows, and so mitigation works need not be so robust as those at the fan head.

6.7 Mitigation options between Waimea and Awatarariki Streams

The hazard here is mainly confined to the area of land south of the railway. The hazard largely is that of falling debris (landslides (debris avalanches) from the adjacent steep slopes). One small area, a small steep fan head midway between Clarke and Simpson Streets (Figure 5.0.1), has an additional hazard of flood and debris-flow inundation. On 18 May, this particular area was subject only to flood inundation, with some sediment deposition. Rain in its upper catchment did not trigger a debris avalanche and so there was no debris flow. This appears to be because the local rainfall intensities were not as high there as they were to the south and west. It is most unlikely that the small catchment above the fanhead experienced sustained 2-mm-per-minute rainfall on 18 May. The deposits shown in Figure 2.2.1 show that debris flows have built this fan, and so we can infer that the conditions needed to trigger them can occur there.

We give the apex of this fan a high hazard rating on three counts: any of extreme flood flow, debris avalanche and debris flow potentially could cause structural damage there. Conventional mitigation work for the hazards at this site would route the creek through a lined, wide, box-shaped channel directly down the centre of the fan, to protect areas on the lower flanks of the fan. The apex of a steep fan generally is unsuitable for any residential use, although homes are found widely around New Zealand on such sites, which are sought after for the panoramic views they provide.

Several debris avalanches fell near to the gorge of Awatarariki Stream, but they appear not to have caused damage. This mostly is because there is not sufficient space between the railway and the hillslope for houses.

Along this entire slope, there is little space for mitigation works against debris avalanches. Acceptance of the high hazard to life and property, or avoidance of the area are the only mitigation options known to work for such situations. The step in slope created by construction of the railway mitigates the otherwise high hazard for properties below it.

Engineering work to mitigate the inundation hazard of floods and debris flows on short steep fans usually involves providing a safe route for debris flows through a deep, lined channel, such as illustrated in Figure 6.6.1. Of course, such works must include an area below to safely receive the debris and water.

Figure 6.6.1 A conventional mitigation works for a steep debris-flow fan near Sarno, Italy, built after a recent disaster. In this example, the works mostly protect vineyards.

6.8 Mitigation options for the lagoons

There are no practical methods to stop sediment coming out of the catchments draining to the lagoons between Matata and the sea. All of the above options to make Matata safer are intended to route fine sediment as quickly as possible from the upper catchments into the lagoons. The lagoons are artificial and ephemeral features, created by diversion of Tarawera River early last century. They are ephemeral because without the large river to episodically flush sediment out of them, they are filling up quickly. If the lagoon system is to be maintained, it can only be maintained artificially by removal of the sediment.

7.0 CONCLUSIONS

- Witness descriptions and the physical evidence indicate that the phenomena that damaged portions of Matata in the vicinity of Awatarariki and Waitepuru Streams were landslides of the type classified as debris flows: dense fluid mixtures of all manner of debris and water. They move very rapidly, and are capable of carrying immense boulders. Boulders up to 7 m across were moved by the debris flows in Awatarariki Stream.
- Evidence in the upper catchments indicates that the primary causative events that inevitably led to the debris-flow damage at Matata were landslips of the type termed *debris avalanches,* triggered by exceptionally heavy rain in the catchments south of Matata. The debris flows directly damaged some homes and property. Other homes and property were damaged by debris floods that extended beyond where the debris flows came to rest. A debris flow is usually accompanied by a debris flood beyond its limits of flow, and the associated debris flood is regarded by technical experts as an integral part of the total debris-flow event.
- The phenomenon that damaged property in the vicinity of Waimea Stream was a debris flood. We were not able to determine whether this debris flood had an associated debris flow in the upper catchment. A debris flood is less damaging than a debris flow, and it can occur in the absence of a debris flow.
- The phenomenon that damaged homes and property in the vicinity of Awakaponga Stream was a debris flood that was a direct consequence of a debris flow that itself caused no direct damage.
- The phenomenon that damaged property in the vicinity of Ohinekoao Stream was a debris flow that reached to SH2. Its associated debris flood damaged the railway and property beyond.
- The landslide phenomena that came directly from the hillside above Matata, and along SH2 to the west of Matata were debris avalanches. These are very similar to debris flows, but they lack a confining channel. Similar features falling into the catchments south of Matata initiated the debris flows there.
- The evidence for debris dams in the catchments, that can still be seen, is from landslides that fell after the debris flows had passed. The highly erosive debris flows cleaned out the valley bottoms, and destabilised the slopes along the channel, causing secondary landslides. Many of these have been larger than the initial landslips that triggered the debris flows.
- The boulders carried by the debris flows came mostly from erosion by the debris flows of boulders previously buried in the bed and banks of the stream channels. They got there by falling from the bluffs above the stream at various times in the past. Most of the harder boulders are derived from strongly welded portions of the Matahina ignimbrite formation. The boulders eroded from the channels already are being replaced by collapse of the steep

slopes. This process will continue. Although the supplies of boulders in the channels have been depleted by the event of 18 May, they have not been exhausted. Further debris flows are possible and likely whenever there is rain with high enough intensity to trigger debris avalanches on steep slopes.

- The earthquake swarm that has been shaking Matata for many months did not contribute to the disaster of 18 May. Landslips that occurred in the 1987 Edgecumbe earthquake were the source of some of the boulders that were carried by the 18 May debris flows. Others fell in landslips on 18 May, but most were already in the bed and banks of the channel from earlier events, and were picked up by the immensely erosive debris flows.
- By their nature, debris flows are more dangerous than floods, and they make the flooding associated with them worse than it otherwise would be without a debris flow. They make the flooding worse for two reasons: (1) they travel faster than the flow of water in the same channel and pick up all of the floodwater in their path, thus delivering water to the catchment outlet faster than would be possible in a simple flood; (2) deposition of sediment from a debris flow can fill the normal stream channel and allow water draining from the debris flow to flood into areas not normally accessible by floodwater.
- Hyperconcentrated flows of sediment-laden water draining from the Matata debris flows caused debris floods. That is, the water was so highly charged with sand and silt that it no longer behaved like normal water. It flowed faster and was more dense, and was capable of moving larger boulders than could be moved by a normal flood flow across the lowland fans at Matata.
- The landslips that initiated the debris flows were triggered by very intense rain, probably in excess of 2 mm/minute that fell in the catchments during a severe thunderstorm. This intense rainfall fell in a narrow band only a few kilometres wide that passed across the catchments to the south of Matata from near the mouth of Ohinekoao Stream to the settlement of Awakaponga. Had this band of rain been some 500 m closer to Matata, a different, and much more devastating outcome might have occurred. The existing debris flows could have been larger, and other catchments also could have poured debris flows into Matata. In addition, there may have been more debris avalanches from the slopes immediately behind Matata. Such events have happened many times in the prehistoric past, and they created the land on which Matata stands.
- Parts of Matata are naturally protected from flooding and debris flows at the present time, but this protection is reducing with each episode of sediment deposition. The protection arises because the ancient debris flows fans were trimmed by Tarawera River, and the streams draining from the catchments to the south of Matata cut deeply into the fan toes, leaving much of the land free from flood risk. The low railway embankment gives some other parts of Matata varying degrees of protection from water and debris floods, by diverting shallow flows. The railway, however, also increases the danger to some areas, because it diverts flows to areas not otherwise at risk.

- There are areas around Matata that are unsafe for habitation. Significant areas of present-day Matata have always been at risk from floods, debris flows, debris floods and debris avalanches. These are wider than the currently affected areas. With engineering works, it is possible to reduce the danger to some areas to levels that are commonly accepted in other areas of New Zealand, but there are other areas where such mitigation is not feasible, and it will be necessary either to accept the risk, or remove dwellings from them. Of course, any area designated as a floodway or debris-flow route will be uninhabitable, but could be used for recreation.
- Because of the location of the railway and SH2, it is not possible to provide effective engineering mitigation of the hazards to Matata without integrating this protection with engineering works associated with the railway and SH2. Of critical concern are the effects of bridge and culvert sizes. Where these are too small or misaligned to safely pass debris flows or debris floods, the resulting obstruction to the flows causes deposition and a somewhat random choice of path for the immediately following debris. If the path of the debris cannot be predicted or controlled, then no mitigation works can be effective elsewhere, and building regulation becomes the only safe option.

8.0 RECOMMENDATIONS

- We recommend that communities in the wider Bay of Plenty area explore the potential of having a locally based, weather-radar system for warning of severe storms.
- We recommend that the Matata community pays attention to the danger of small steep streams, and allocates adequate space for them to pass safely through Matata.
- We recommend that the community at Matata consider the feasibility of having debris-flow detention basins on Waitepuru and Awatarariki Streams.
- We recommend that a bund be constructed on the Matata side of Awatarariki Stream floodway.
- We recommend that Waitepuru Stream be diverted to a course that bypasses Matata to halt the current trend of reducing safety from flooding.
- We do not know if debris-flow mitigation work is warranted at Waimea Stream, but recommend that adjacent residents be told that there is a danger there from debris flows.
- We recommend that the hazard from inundation by hyperconcentrated flows from Waimea Stream be mitigated with an adequately designed railway culvert, and erosion-resistant channel downstream.
- We recommend that residents of the properties landward of the railway between Simpson and Clarke Streets on Pakeha Road, be told of the (high) risks of inundation and falling debris (landslides) at those sites. We recommend that mitigation options for these sites be considered. The sites may need to be abandoned if mitigation to an acceptably low risk is impractical.

- We recommend realignment and upgrading of the SH2 and railway bridges at Ohinekoao Stream if property on the seaward side of the railway is to be protected from debris flow damage from this stream.
- We recommend a combined approach between the authorities controlling the railway, SH2 and the Matata community to provide overall effective flood and debris-flow mitigation works.
- We commend the initiative taken at Awakaponga Stream, but recommend that the boulder bund be extended a little further, and covered with soil.
- We recommend further, less robust bunds lower on the fan of Awakaponga Stream to more adequately protect other dwellings there.

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APPENDIX 1 MAY 2005 RAINFALL EVENT

	Rainfall (mm)										
	17-May-05				18-May-05				19-May-05		22-May-05
Site	**15 min max.**	**30 min max.**	**1 hour max.**	**24 hour total**	**15 min max.**	**30 min max.**	**1 hour max.**	**24 hour total**	**24 hour total**	**Event total**	**24 hour total**
Western Bay Catchments											
Tuapiro	6.5	10.0	13.0	70.5	3.0	4.5	7.0	25.0	11.0	106.5	24.5
Waipapa	2.5	4.0	7.5	42.5	3.5	3.5	5.0	31.0	10.5	84.0	41.0
Tauranga Airport	-	-	3.0	14.0	-	-	58.0	346.2	5.4	365.6	-
Kaituna Catchment											
Whakarewarewa	1.5	2.0	2.5	8.0	2.0	3.5	6.0	33.0	4.0	45.0	11.0
Rotorua Airport	-	-	3.6	12.8	-	-	8.4	62.2	3.2	78.2	
Kaharoa	3.0	4.5	7.5	37.5	4.0	5.5	9.0	65.5	12.5	115.5	31.0
Mangorewa	3.0	5.0	8.5	32.5	22.0	41.0	73.0	220.0	12.5	265.0	34.5
Te Matai	4.0	7.0	9.5	36.0	4.0	34.5	57.5	216.0	9.5	261.5	15.5
Te Puke AWS	-	-	5.0	25.2	-	-	24.4	158.0	4.8	188.0	-
Central Catchments											
Pongakawa	4.5	7.0	12.5	31.5	11.5	12.5	16.5	126.5	15.5	173.5	34.0
Ohinekoao	6.0	9.5	12.5	39.5	13.0	23.5	44.5	250.0	44.0	333.5	36.0
Plains											
Tumurau Lagoon	4.0	7.0	9.5	37.5	21.0	39.0	71.0	274.5	33.0	345.0	40.5
Awakaponga	5.0	7.5	9.0	39.0	30.5	58.0	94.5	302.0	20.5	361.5	25.0
Thornton	2.5	4.5	8.0	28.5	17.5	32.5	44.0	109.5	22.5	160.5	24.0
Whakatane Airport	-	-	6.8	22.6	-	-	28.2	80.4	10.8	113.8	-
Rangitaiki Catchment											
Kokomoka	1.0	1.5	1.5	8.0	1.5	2.0	3.0	17.5	2.0	27.5	18.5
Whirinaki	2.0	3.5	4.5	13.5	12.0	16.5	20.5	76.5	8.5	98.5	11.5
Aniwhenua	3.0	4.0	6.0	19.5	7.0	11.0	15.5	109.5	12.0	141.0	26.0
Waimana Catchment											
Huiarau	2.0	3.5	6.5	21.5	7.5	11.0	14.0	47.5	8.5	77.5	27.5
Ranger Stn	1.5	3.0	5.5	13.0	4.0	5.0	6.5	37.5	6.0	56.5	50.0
Waioeka Catchment											
Koranga	1.0	2.0	3.5	14.5	1.0	2.0	3.0	12.0	2.0	28.5	33.5
Cableway	1.5	2.0	3.0	9.0	3.0	4.0	5.5	20.0	4.5	33.5	56.5
Mouth of Gorge	1.0	2.0	3.0	6.0	7.0	10.5	13.5	22.5	8.0	36.5	38.5
Otara Catchment											
Pakihi	1.0	2.0	3.0	4.5	2.0	3.0	4.0	9.0	4.5	18.0	45.5
Tutaetoko	1.0	2.0	3.5	9.0	6.5	8.5	12.0	21.5	3.5	34.0	37.0
Browns Bridge	1.0	1.5	2.5	5.0	4.5	5.5	7.5	15.0	6.0	26.0	38.5
Opotiki Wharf	1.0	1.0	1.5	4.0	4.0	7.0	7.5	19.0	9.0	32.0	26.0

Note: - data unavailable.

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